Highlights of experimental results and open theory-related aspects concerning specific (B)SM searches

Luca Perrozzi (ETH Zurich)

Mainz, March 05th 2018

~1y ago: different topic, similar issues

W mass
CMS status report

W mass workshop

Mainz, Feb. 9th 2017

(some of the) Open questions

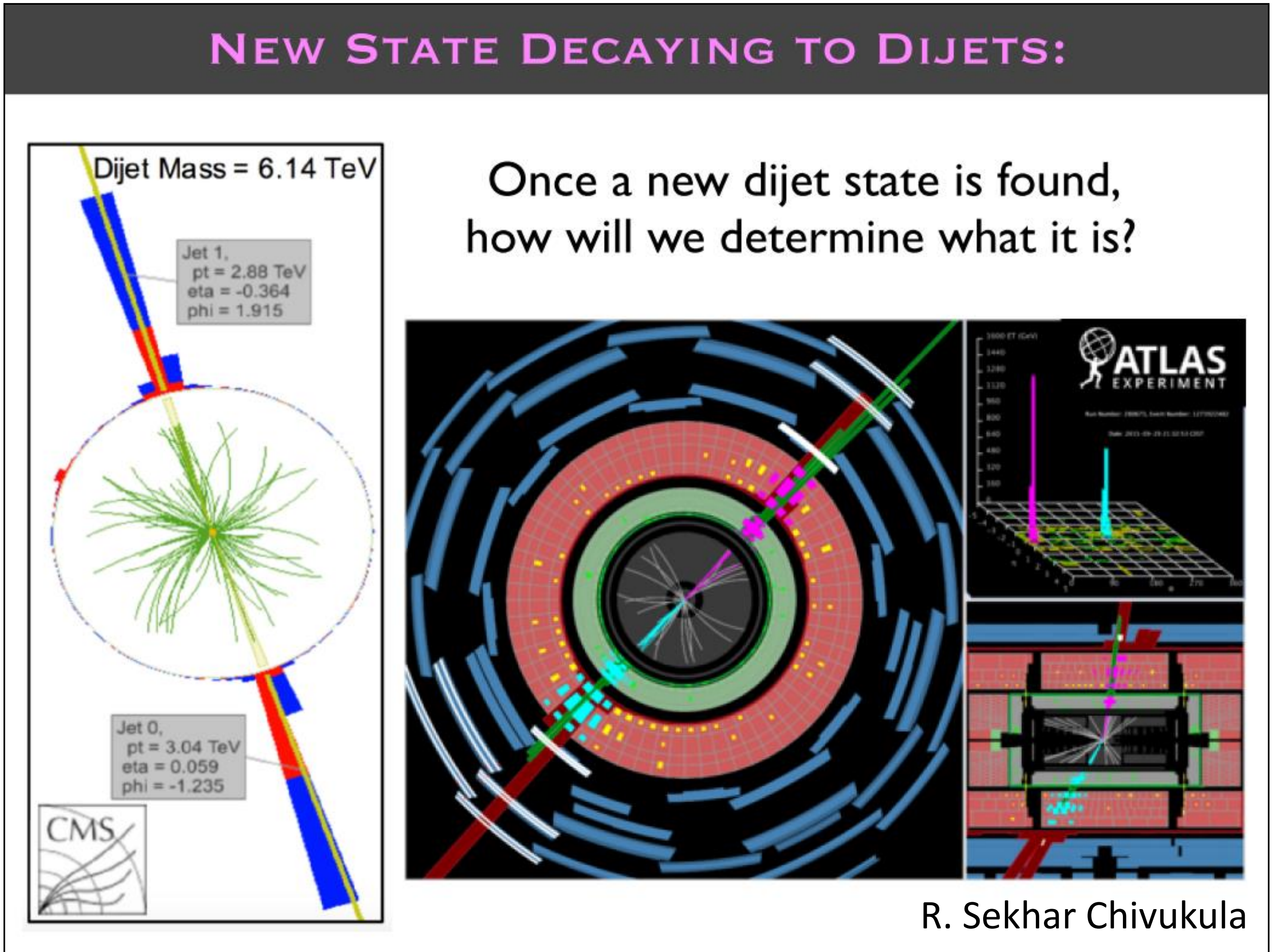
- The Underlying Event-Parton Shower-PDF-Resummation triangle problem
  - What to correlate? How?
- Is the Pythia only tuning satisfactory?
  - What can we learn from that?
- Can we content ourselves with an effective description or shall we try to profit more from the higher order QCD corrections?
  - How?
- How is the Z tuning correlated to the W?
  - The more "effective" the description, the less theoretically motivated any given choice of correlation scheme can be.
- Are the theory uncertainties of ATLAS fair? Underestimated?
  - We don't know either way until we have a more coherent and theoretically motivated model

Content

- **What and how are we searching for BSM?**
  - What and how will the searches evolve?
- **SUSY searches and extrapolation systematics**
  - Top modeling and parton shower uncertainties
- **The Higgs case: precision vs sensitivity**
  - Tails, fixed order calculations and boosted regions
- **The V+jets ratio case: SM background for DM searches**
  - QCD and EWK systematics, including correlations!
- **More than limits**
- **PDF for BSM and photon induced processes**

The “problem” (I)

- Many **experimental** talks on BSM start more or less like this
  - Difficult to reconcile phase space to search for, model independency and interpretation of a new signal



The “problem” (II)

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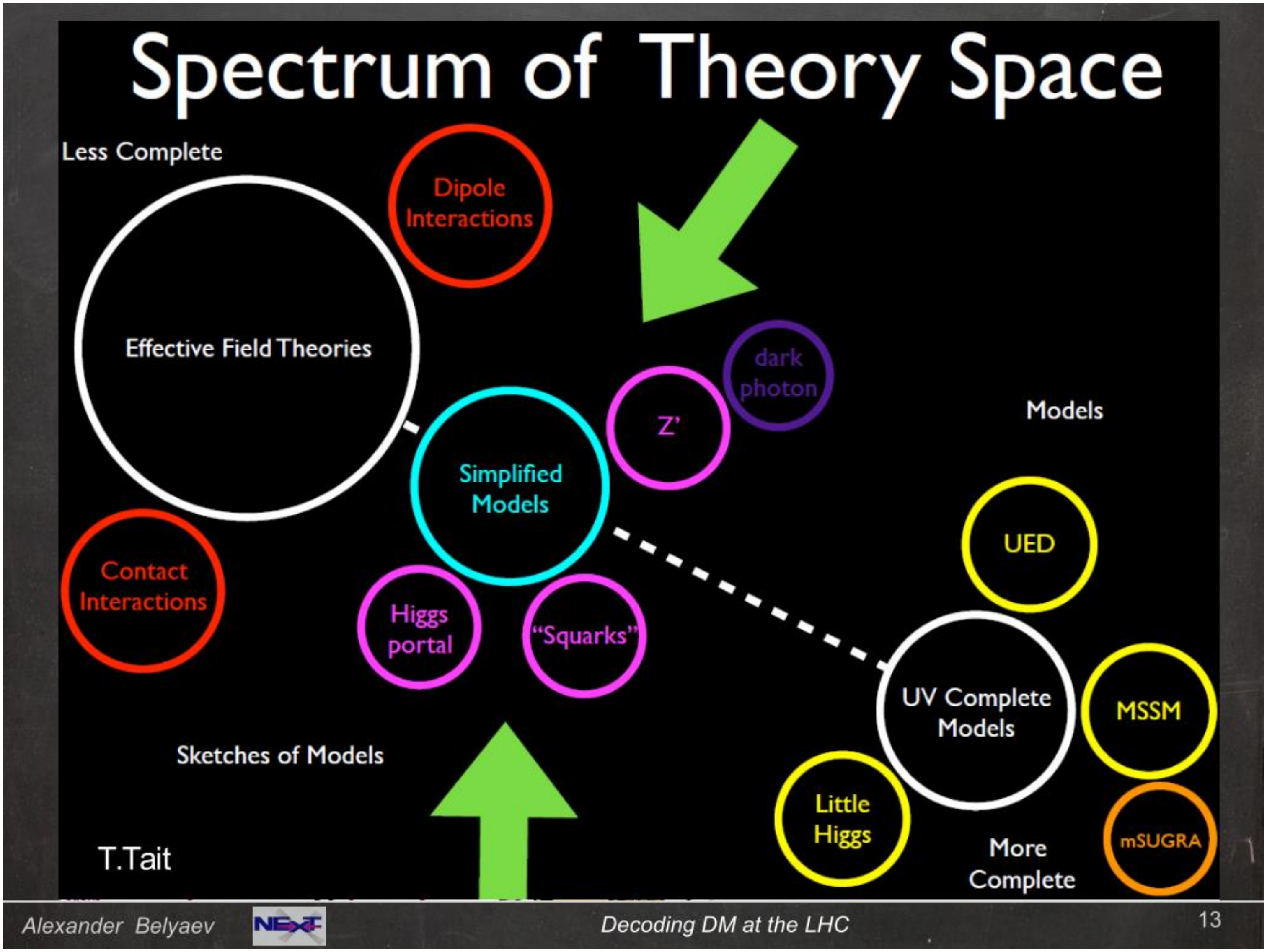
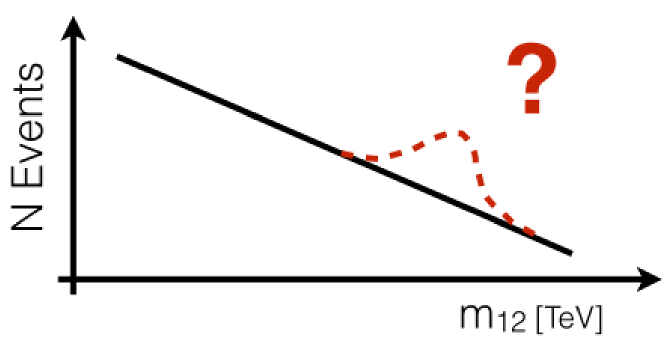
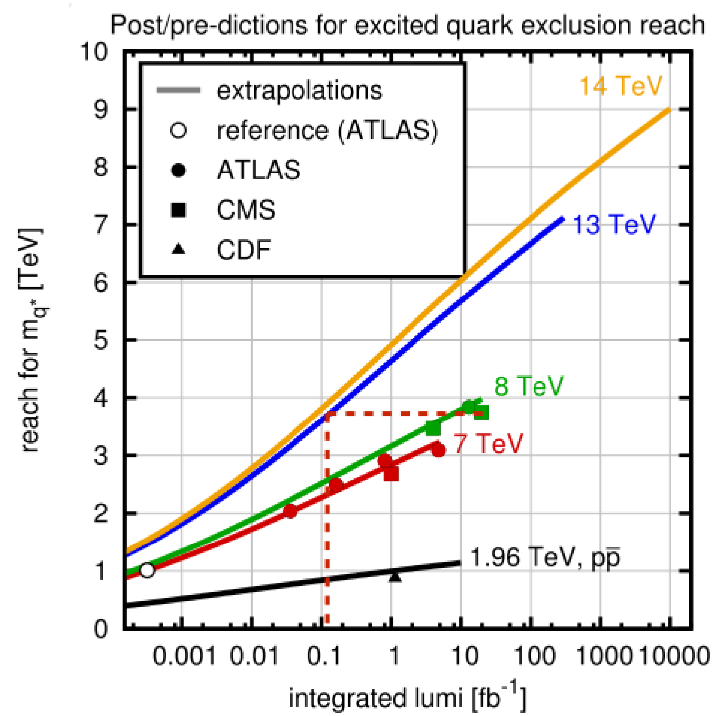


Back to basics:
what (and how)
are we searching for BSM?

Probing Physics Beyond the Standard Model with Precision

- **Why are we here?**
- **The "Optimistic" approach didn't work out as hoped**
  - Run the machine, collect data, something will pop-up
  - At the beginning of the LHC, mostly "Reference Analyses" used
    - Theory-independent, simply defined by final state
    - Quick turnaround with higher statistics and/or higher energy





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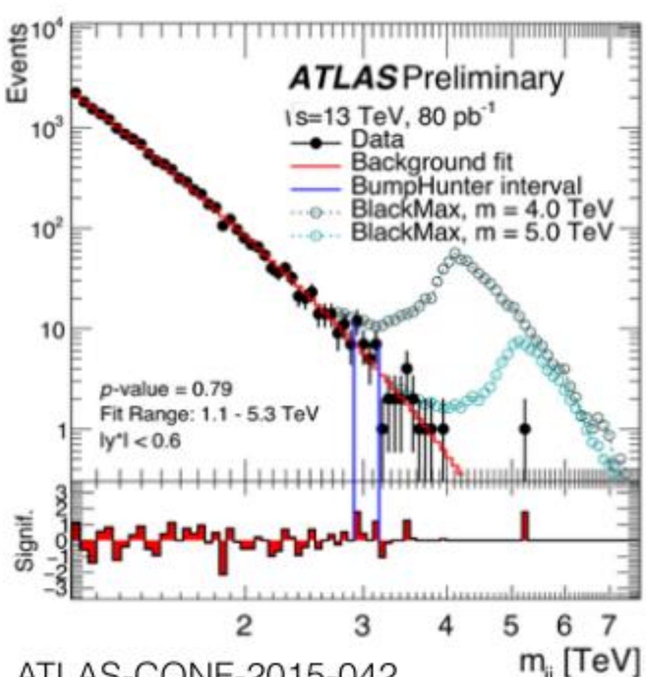


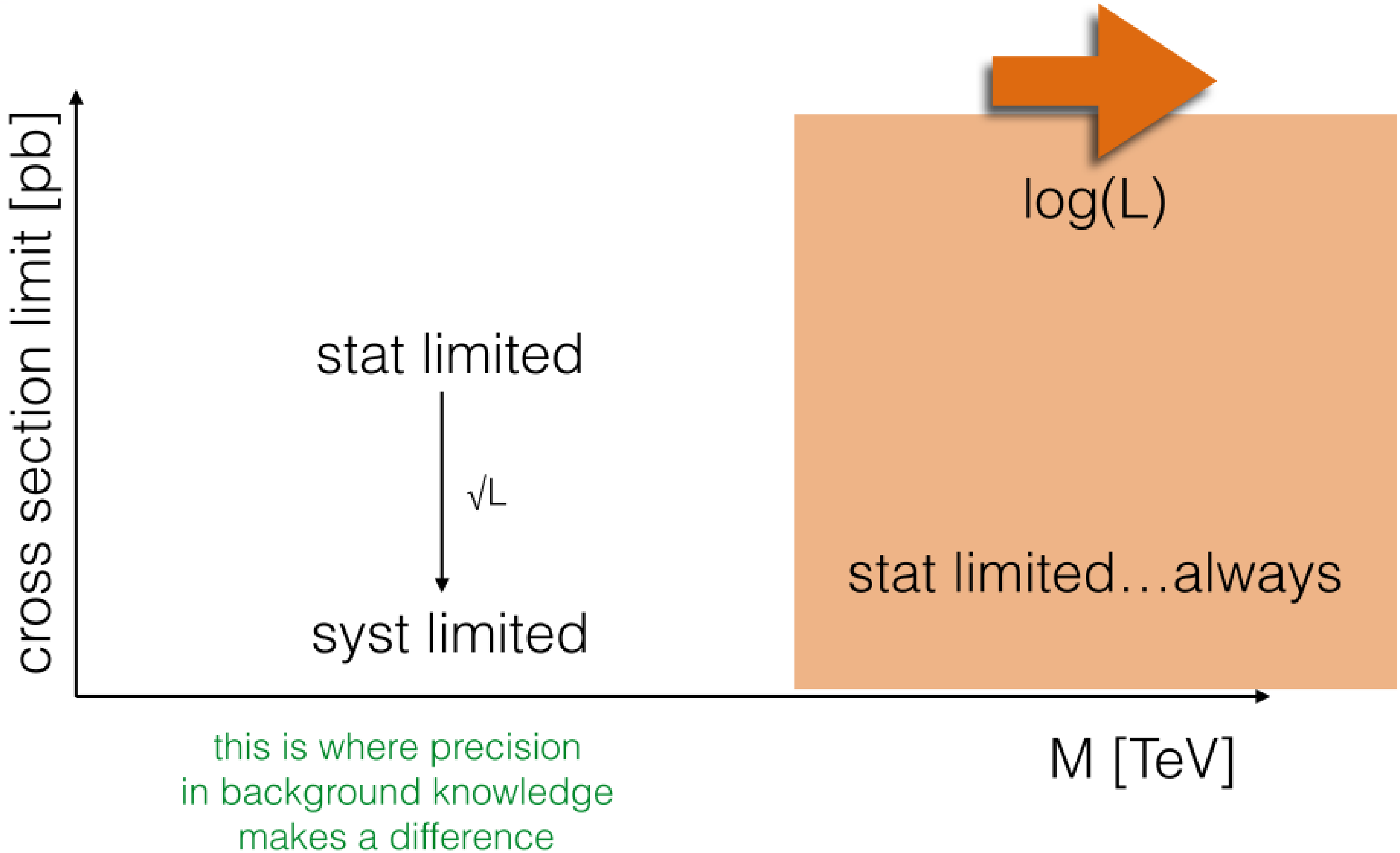
ATLAS-CONF-2015-042

model QCD with fit:

$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

largest concern: smoothness

Search lifetime



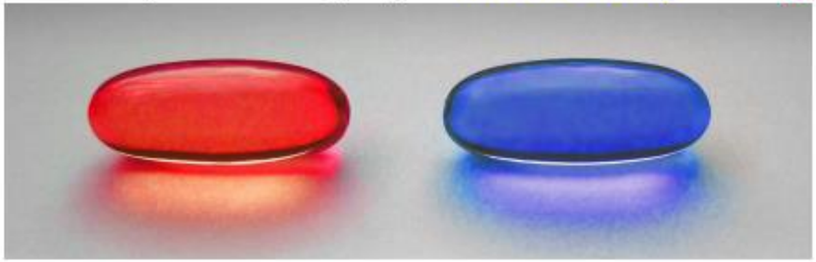
psychology - how low can you go??

Are we looking everywhere?

- most new physics searches are designed to be sensitive to deviation from the SM expectation in a broad phase-space
- in specific cases of extremely low cross sections the optimization is more targeted

To be open to any possibility - cannot stay too specific in new physics searches

Choose which price to pay: sensitivity vs. generality



- can check performance of a general new physics search on a new model as an example

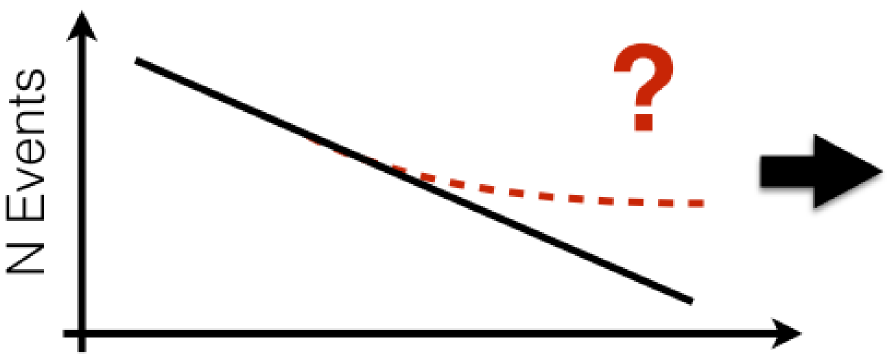
Lesya Shchutska

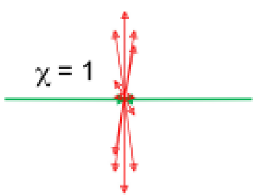
Probing Physics Beyond the Standard Model with Precision

- **Life changed after the the first year of LHC Run2**
  - No sign of BSM, even with large jump in energy
    - We will not experience another such a jump (8→13 TeV) for some time…
- **Low hanging fruits are basically over…**
  - Search for spectacular, experimentally difficult signatures
    - **→ Perfect excuse to avoid the need for better theory**
  - Squeeze every bit of the available (and future) data
    - Plethora of theories with “unusual” and “difficult” signatures
    - Start to investigate more and more extreme phase spaces
    - **Need to fight with overwhelming SM backgrounds**
      - **Need very precise knowledge of SM processes**

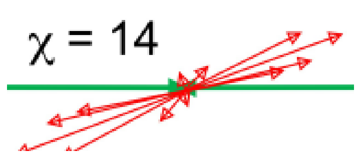
Besides Bumps

- The simplicity of the bump hunt leaves a weakness
  - insensitivity to non-resonant behavior
- **Complementary search needed!**



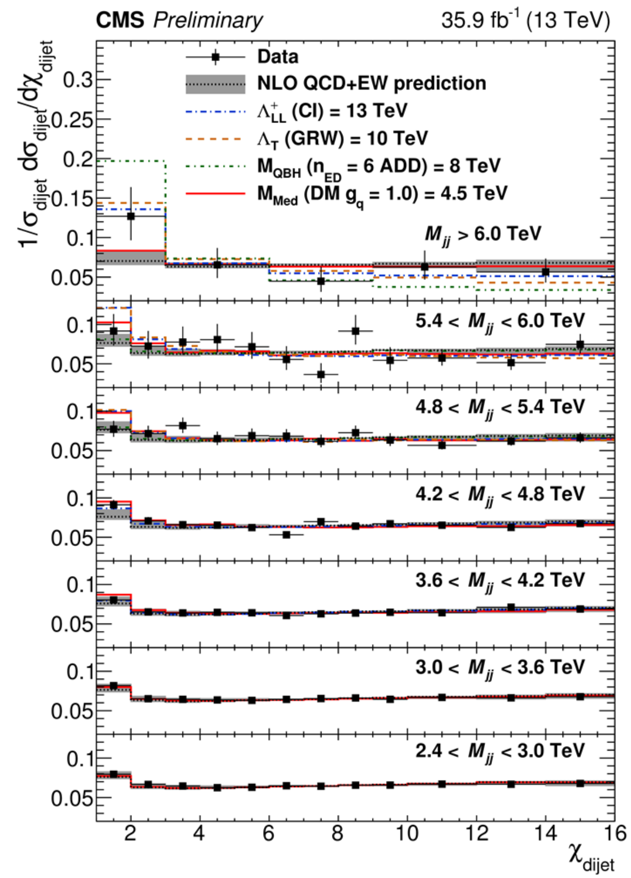


New physics = isotropic decays



Rutherford scattering

CMS-PAS-EXO-16-046

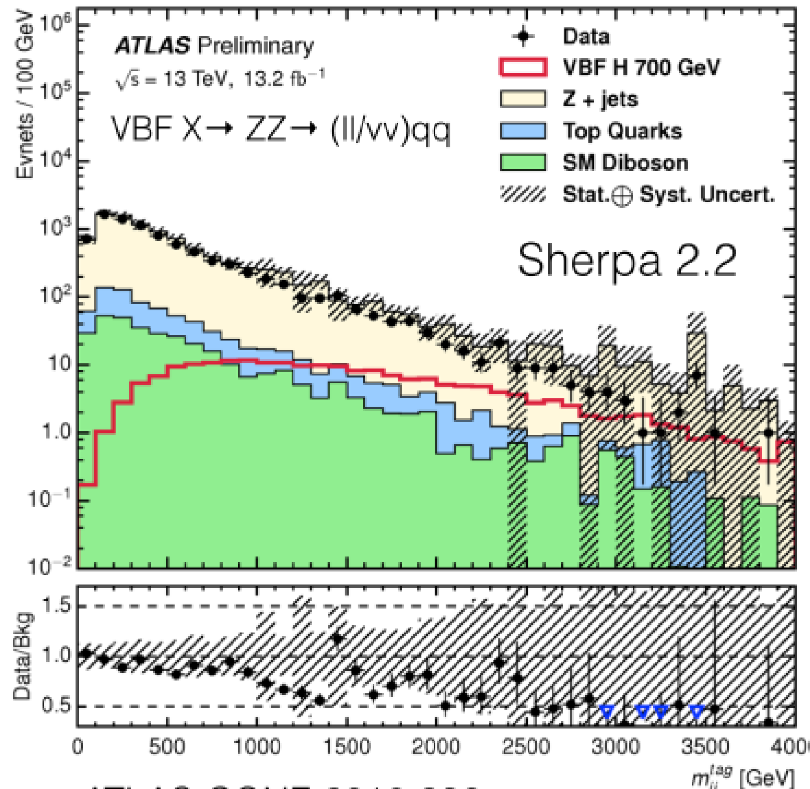


$$\chi = e^{2y^*} = e^{\Delta y} \sim 1+\cos\Theta^*/1-\cos\Theta^*$$

In one word: mostly extremes

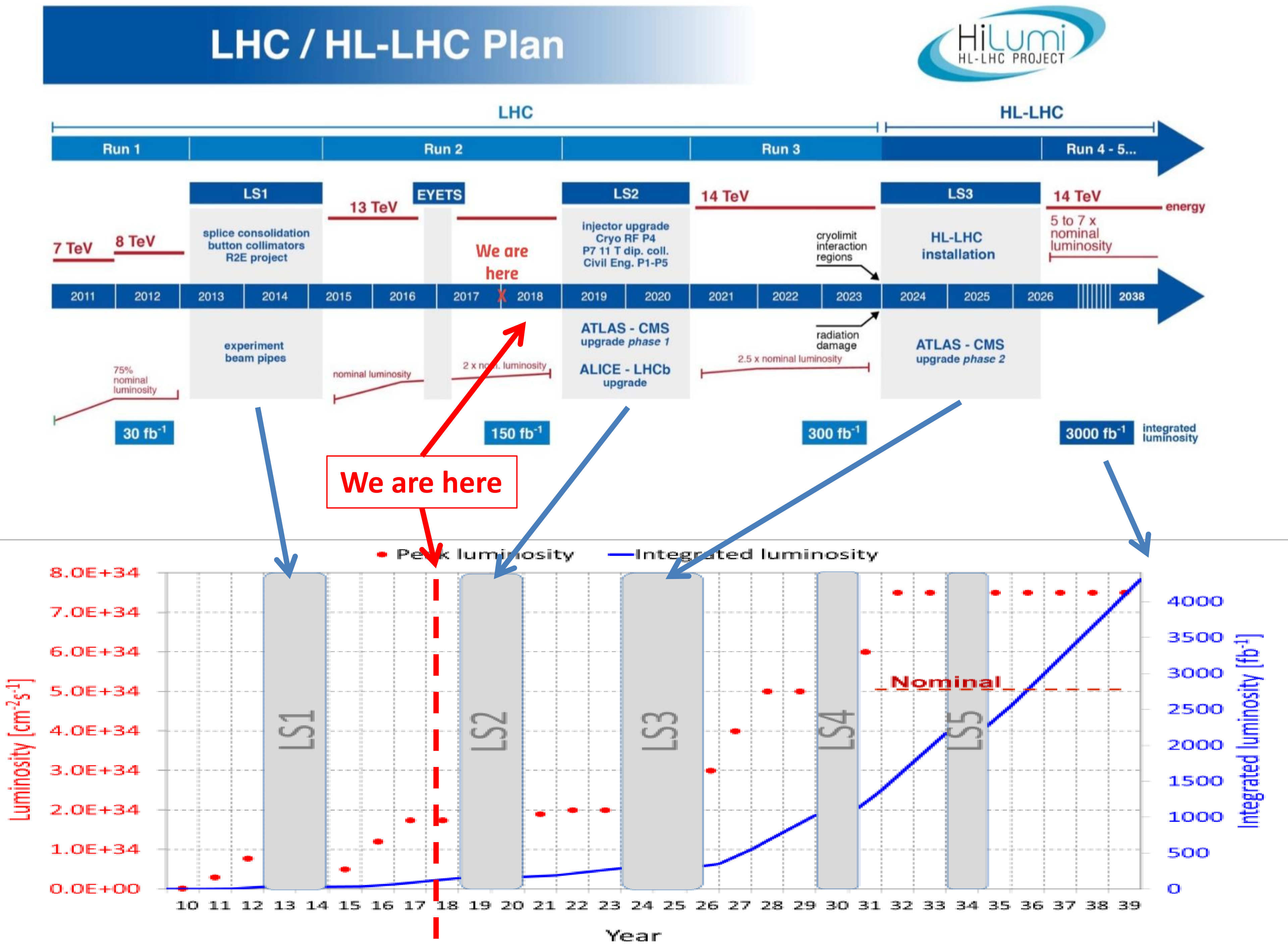
- *Many BSM searches live in the **extremes** of phase space*

- Dependence on:
  - **top p_T** in top pair production events
  - **V p_T** in V+Jets events
  - **high jet multiplicities** in top and V+jets events
  - **VBF** phase-space



ATLAS-CONF-2016-082

LHC / HL-LHC Plan



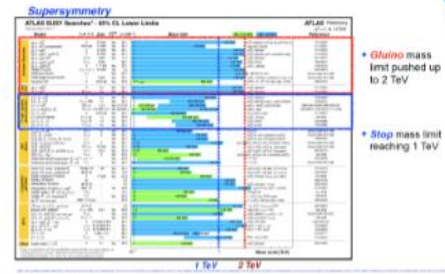
Seeking for precision?

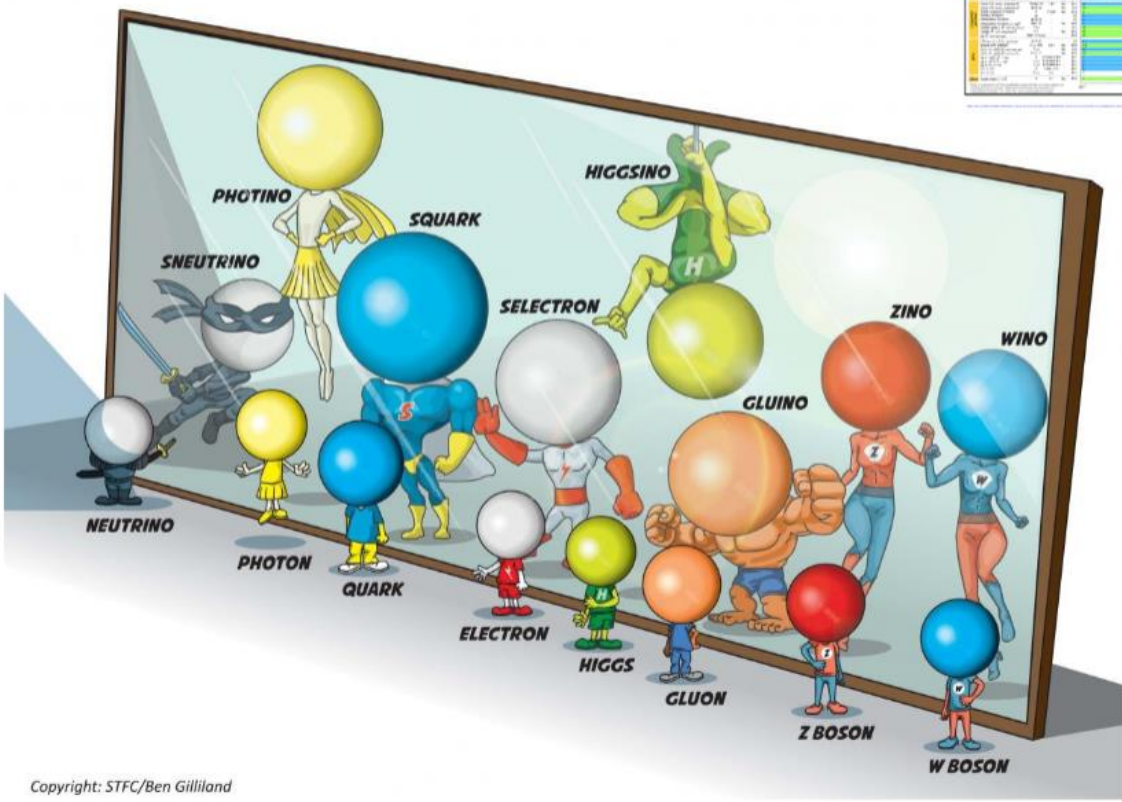
SUSY Searches and extrapolation systematics

Searches for light squarks and gluinos sensitive beyond 2 TeV

Searches for stop quarks reaching 1 TeV

Naturalness being challenged





Strong SUSY

Stop Searches

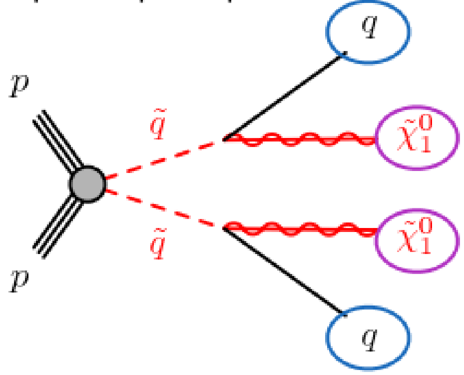
Electroweak SUSY

NO SUSY? ;-)

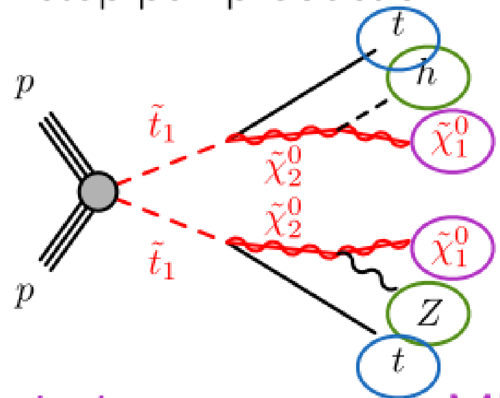
Oliver Stelzer-Chilton, HEP18

Often final states are (very) complicated

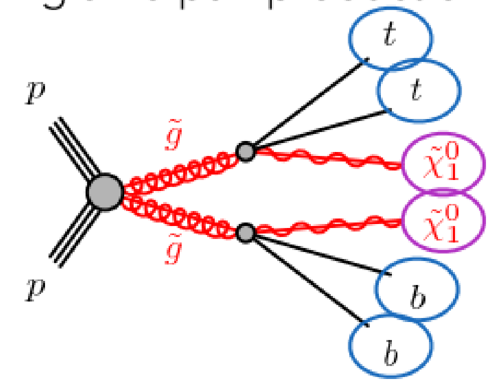
squark pair production



stop pair production



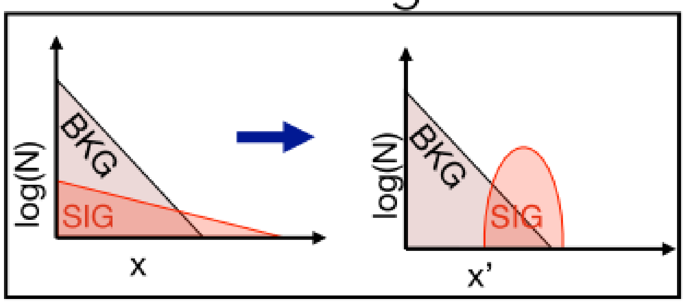
gluino pair production



LSPs: missing energy → MET

large hadronic activity, multiple jets, multiple b-jets, leptons, photons …

Missing information: impossible to fully reconstruct event



most analyses use kinematic discriminating variables to improve S/B ratio

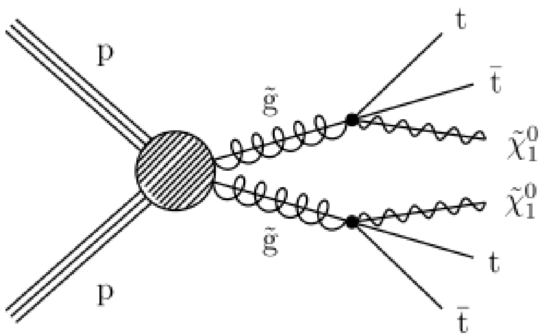
Summary: large phase-space to cover (signal regions), large number of signatures (different analyses), possible to use different discriminating variables

Crucial and ambitious program by LHC experiments

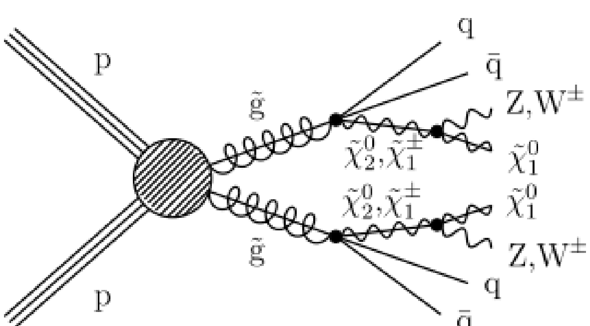
Many dimensions to keep under control

SUS-16-033

CMS multijet, zero-lepton

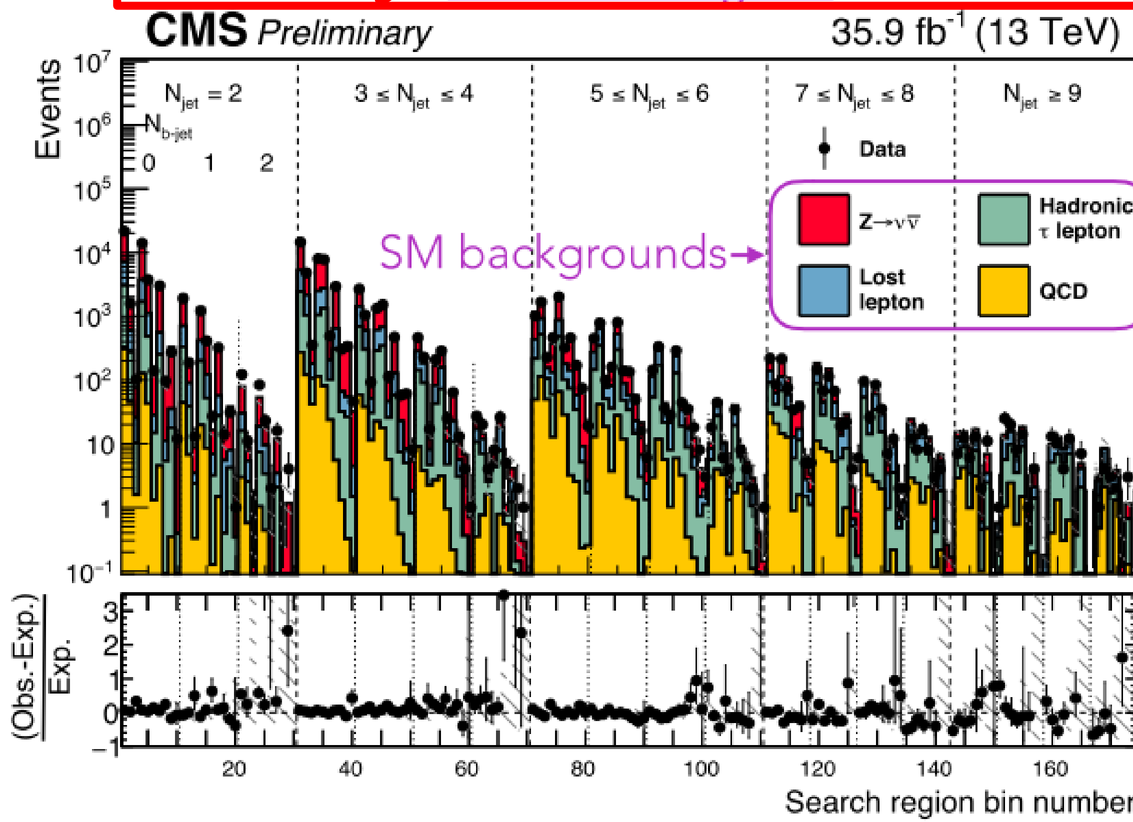


Probe different gluino decays



4-dimensional search in: N_{jets}, $N_{b\text{-}jets}$, H_T, H_T^{Miss}

174 search regions

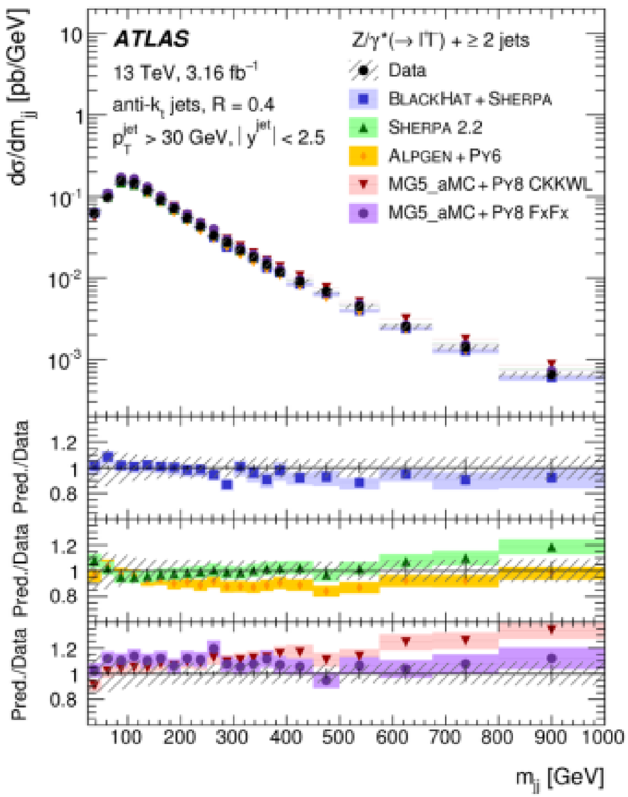


No significant deviations from SM expectation

Meaningful & Harmonized syst

- **Modeling systematics are quite tricky business i.e. top p_T**

- An analysis might:
  - compare 1 generator in 2 settings
  - compare 2 generators
- This is *~arbitrary* and tricky especially when used in modern statistical tools in which these comparisons represent 1 sigma systematics and can be profiled
- Procedures are **not uniform** at ATLAS & CMS.
  - i.e. ttbar/single top interference



- Are recipes "**correct**" or "**complete**"? Items missing, double counted, etc?

Extrapolation syst and top modelling

Systematic uncertainties

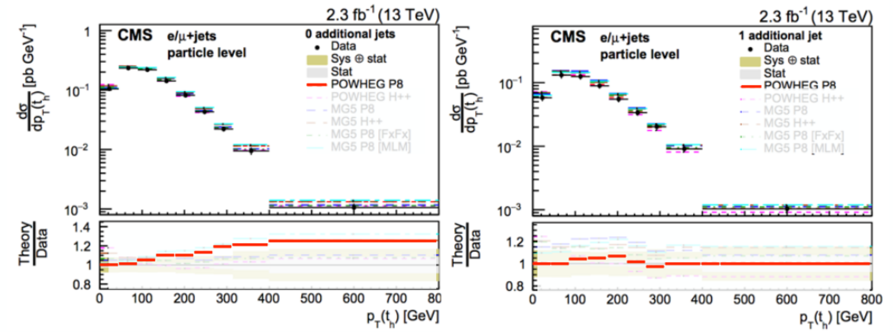
CMS Prescriptions

- Tricky to make definitive list, prescriptions vary with $\sqrt{s}$, time, and analyses.

	RUN 1	RUN 2
Scale	MG5 Q^2 variations	POWHEG μ_R, μ_F variations
Matrix Element	POWHEG -vs- MG5	POWHEG -vs- FxFx
ME - PS	Threshold variatons.	hdamp variations
Hadronisation	b-frag., semi-leptonic B decays, HW6 vs PY6 JER	HERWIG++ -vs- PYTHIA8
Non-perturbative	Tune variations	CUET2P8M4
PDF	CT10 variations	CT14/NNPDF30 variations
Other	Mass variations and pT(t) reweighting	

Jay Howarth, CMS+ATLAS MC workshop '17

Top p_T modelling (Particle Level):



- Measured with 0,1,2,3+ additional jets
- Some interesting shape changes as Njets is probed (e.g. POWHEG P8 in 0 jets vs 1 additional jets).

Outlook — LHCTopWG

Towards combinations:

- Work ongoing for understanding 8 TeV data.
- Combinations planned for 8TeV (parton) and 13 TeV (particle).

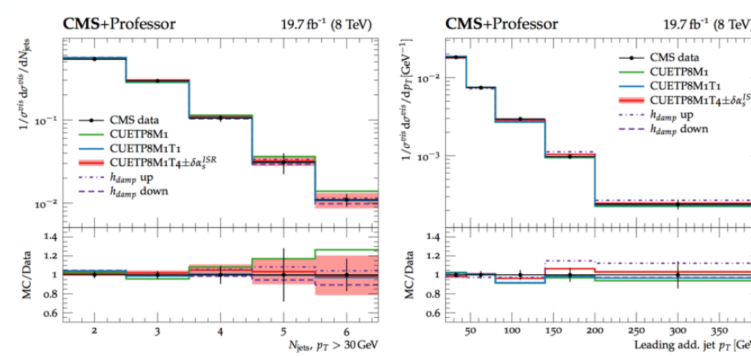
Comparison of results

- Need to carry out full combination to understand agreement between ATLAS and CMS Run1 data.
- Work starting now to also do combinations on 13 TeV data.

POWHEG Tuning

New Tune results:

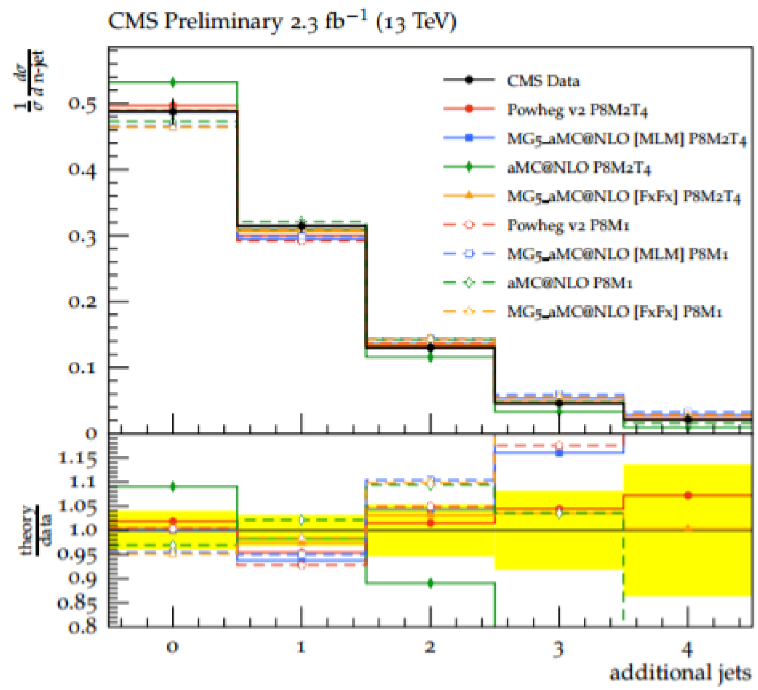
$$h_{\mathrm{damp}} = 1.581^{+0.658}_{-0.585} \times m_t, \qquad \alpha_s^{\mathrm{ISR}} = 0.1108^{+0.0145}_{-0.0142}$$



- Data prefers lower setting of α_S(ISR) and higher setting of hdamp.

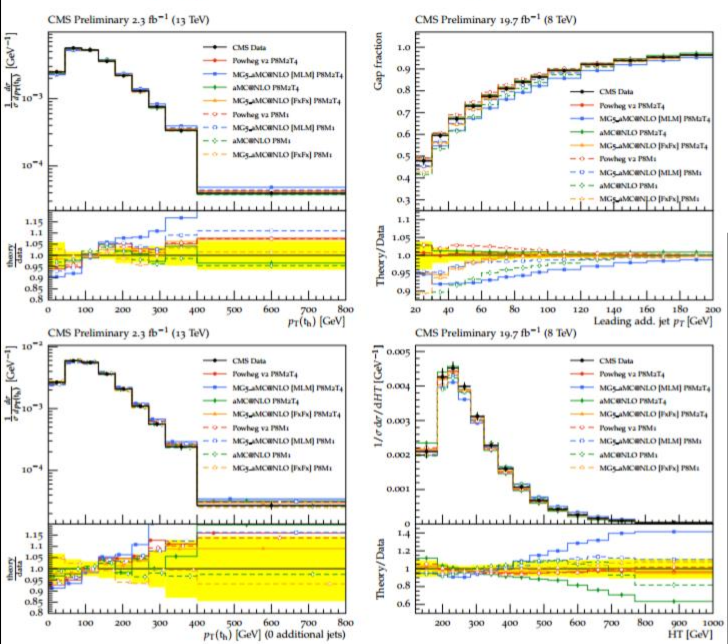
Extrapolation syst and top modelling

- Why to care about tunes?
  - Because it affects the high p_T regime too…
  - For instance by changing Pythia's α_s^{ISR} to match the number of jets distribution in data
  - This impacts ALL other processes, like DY
    - Some things we understand, some else we don't (can't) yet



The new tune is able to describe UE and MB observables at the same time with a lower value of α_S^{ISR}

Top-quark distributions and global event variables at 13 and 8 TeV



Many curves

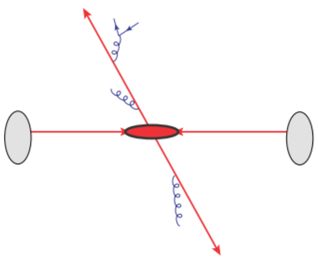
- (full) X+CUETP8M2
- (dashed) X+CUETP8M1

with X = MC from previous slide

4. The new tune gives an overall good description of data in the top sector at 13 TeV for reference MC used in CMS
5. Depending on the matrix element used and the type of matching, data description changes
   - Powheg+Pythia8 and MG5_aMC@NLO [FxFx] with new tune describe all distributions except top p_T (top p_T mismodeling independent of α_S^{ISR} or UE)
   - When applied to MG5_aMC@NLO in MLM configuration, new tune gives bad results.
6. Many more plots in TOP-16-021

perturbative uncertainties in MC generators

Sources of uncertainty & correlations



Uncertainties:

Short-distance cross section:

μ_r^H, μ_f^H, PDF^H, α_s^H

Parton shower:

μ_q^{PS}, μ_r^{PS}, μ_f^{PS}, μ_{cut}^{PS}, PDF^{PS}, α_s^{PS}

Scales: the root of all evil ;-)

...correlated with:

μ_f^H with shower starting scale

μ_f^H, PDF^H with MPI

μ_q^{PS}/μ_f^H and PDF^{PS}/PDF^H

μ_r^{PS}/μ_r^H and α_s^{PS}/α_s^H for NLO+PS

μ_{cut}^{PS} with "string $p_\perp$" & "primordial $k_\perp$"

1. Parton showers "undo" PDF evolution.
2. Short-distance x-sections for matching assume certain PS settings.
3. Hadron p_Ts can be non-perturbative, or inherited from partons

perturbative uncertainties in MC generators

Towards uncertainty recommendations?

Goal: Find consensus how to vary μ_f^H, μ_r^H and μ_q^{PS}.

If we find consensus, can we add μ_r^{PS} and μ_f^{PS} to the mix?

One possible way to find consensus could be to adopt conservative consistency conditions, e.g.:

◇ Backwards evolution of initial state showers allows only small differences of μ_f^H and μ_q^{PS}

perturbative uncertainties in MC generators

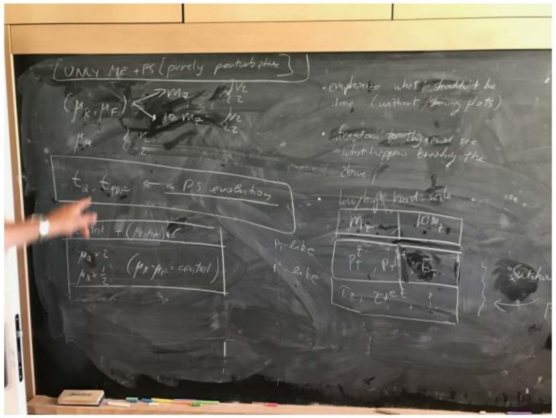
- probably we're not yet in the position of addressing this issue properly, for the scales entering the PS evolution :-(
- but we all agree on the allowed variations for the other scales

★ plan: detailed comparison of several MC generators. We'll look into Drell-Yan:
  - more people can participate
  - try to look at several observables, without including non-perturbative effects
  - hopefully the setup we have should allow to expose possible interesting features
- by having a comparison with analytic resummation, hopefully we'll gain some insight on how to address the original question

Emanuele Re, LH17

perturbative uncertainties in MC generators

we have discussed...



...and agreed...

⇒ so hopefully this will be done

The Higgs case: precision vs sensitivity

Higgs as a BSM probe: precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

Most important message for the next 20y of Higgs physics

$$O = |\langle f|L|i\rangle|^2 = O_{SM}\left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

M. Mangano HC16

For H decays, or inclusive production, $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

$\Rightarrow$ precision probes large Λ

e.g. $\delta O = 1\% \Rightarrow \Lambda \sim 2.5$ TeV

For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

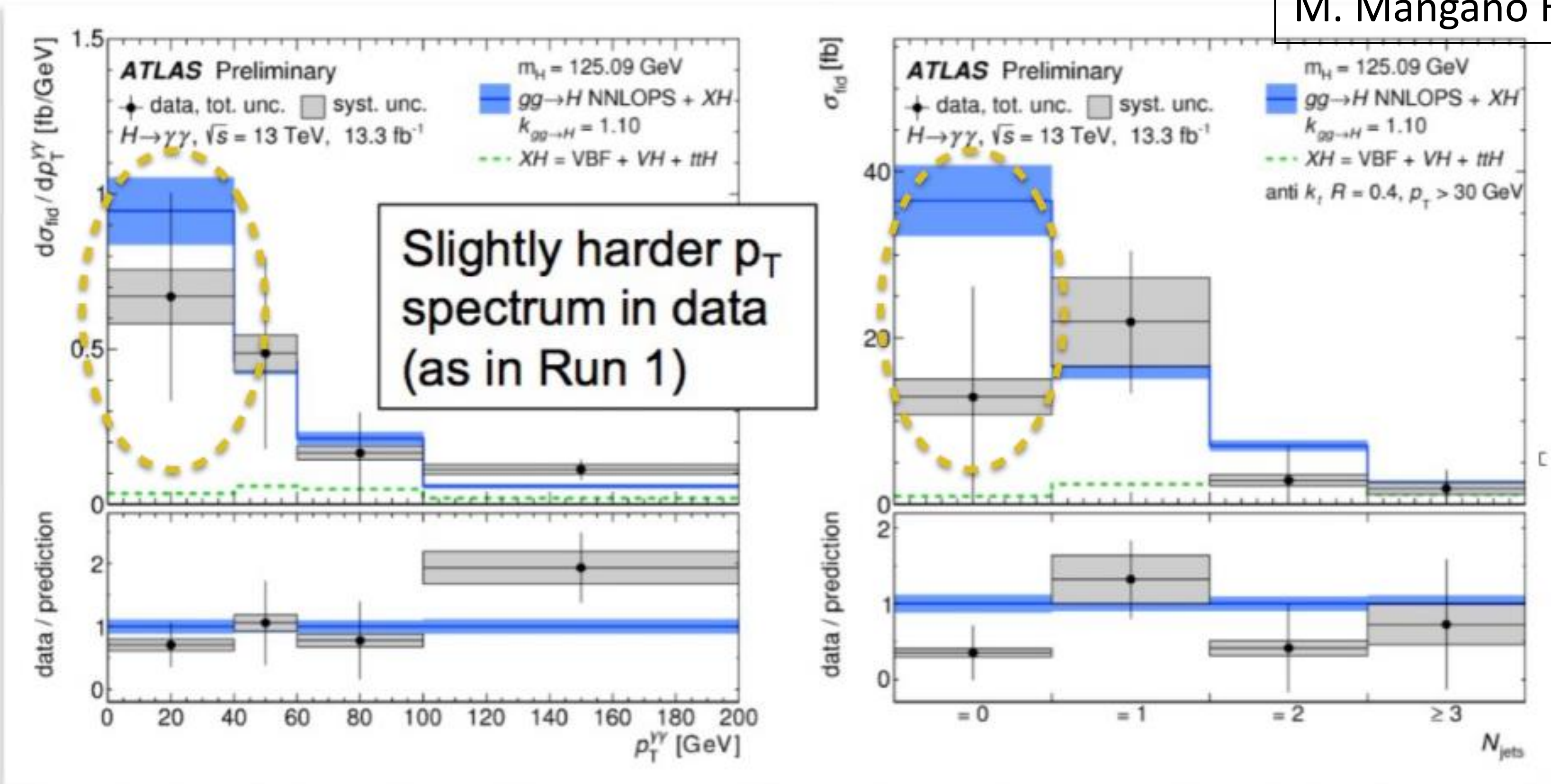
$$\delta O_Q \sim \left(\frac{Q}{\Lambda}\right)^2$$

$\Rightarrow$ kinematic reach probes large Λ even if precision is low

e.g. $\delta O_Q = 15\%$ at Q=1 TeV $\Rightarrow \Lambda \sim 2.5$ TeV

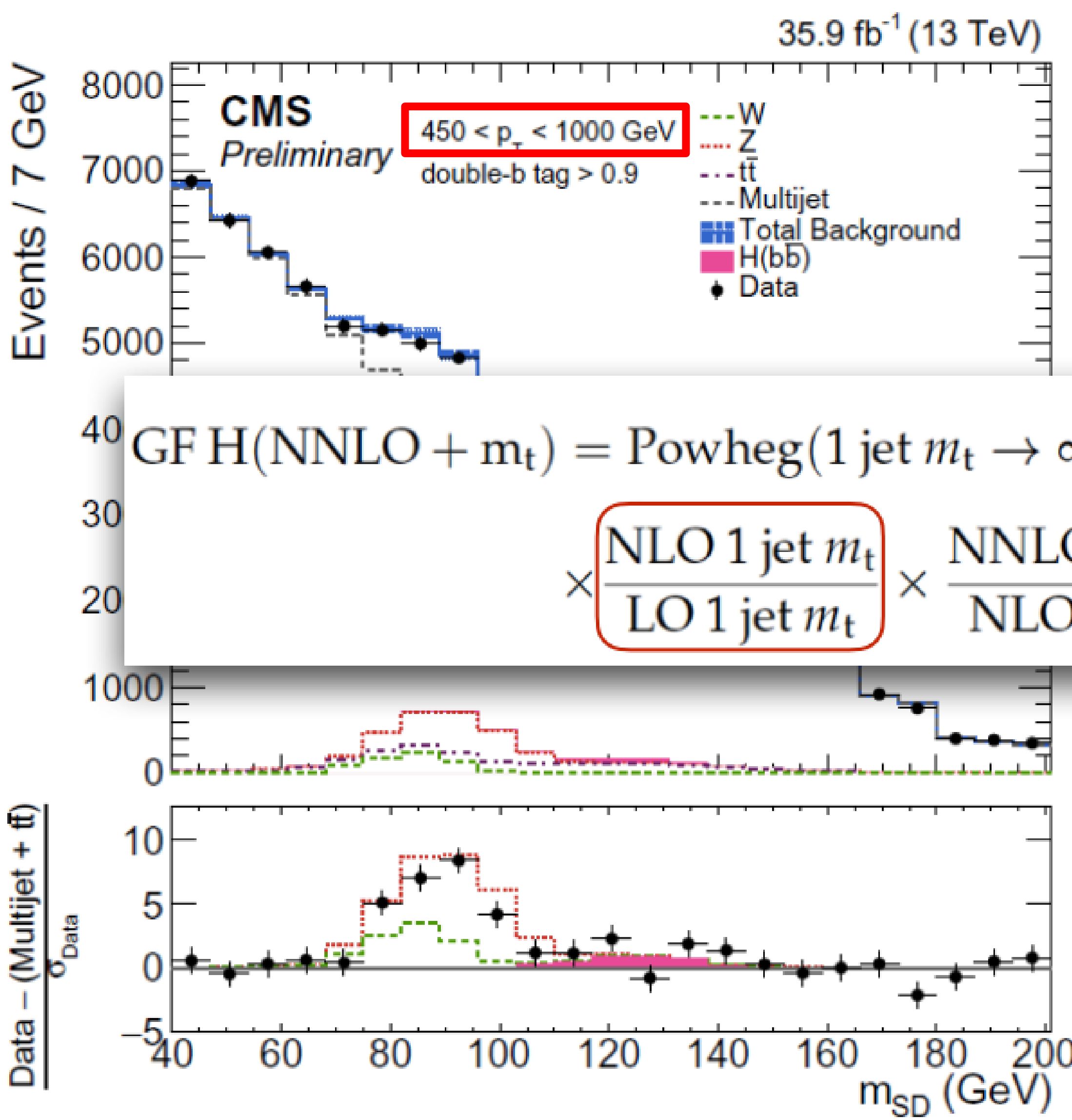
When in trouble, go differential…

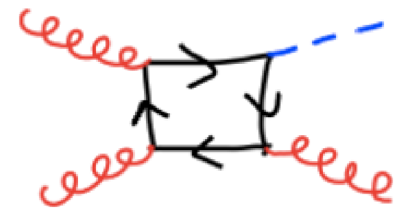
M. Mangano HC16



- δstat ~ 5 δexp => ~25xL ~300fb^{-1} to equalize exp&stat uncert'y
- O(ab^{-1}) will provide an accurate, purely exptl determination of p_T(H) in the theoretically delicate region 0-50 GeV, and **strongly reduce/suppress th'l modeling systematics affecting other measurements (e.g. WW*)**
- More in general, a global programme of higher-order calculations, data validation, MC improvements, PDF determinations, etc, will push further the TH precision….

Higgs @ large pT and the use of k-factors





only known to LO!

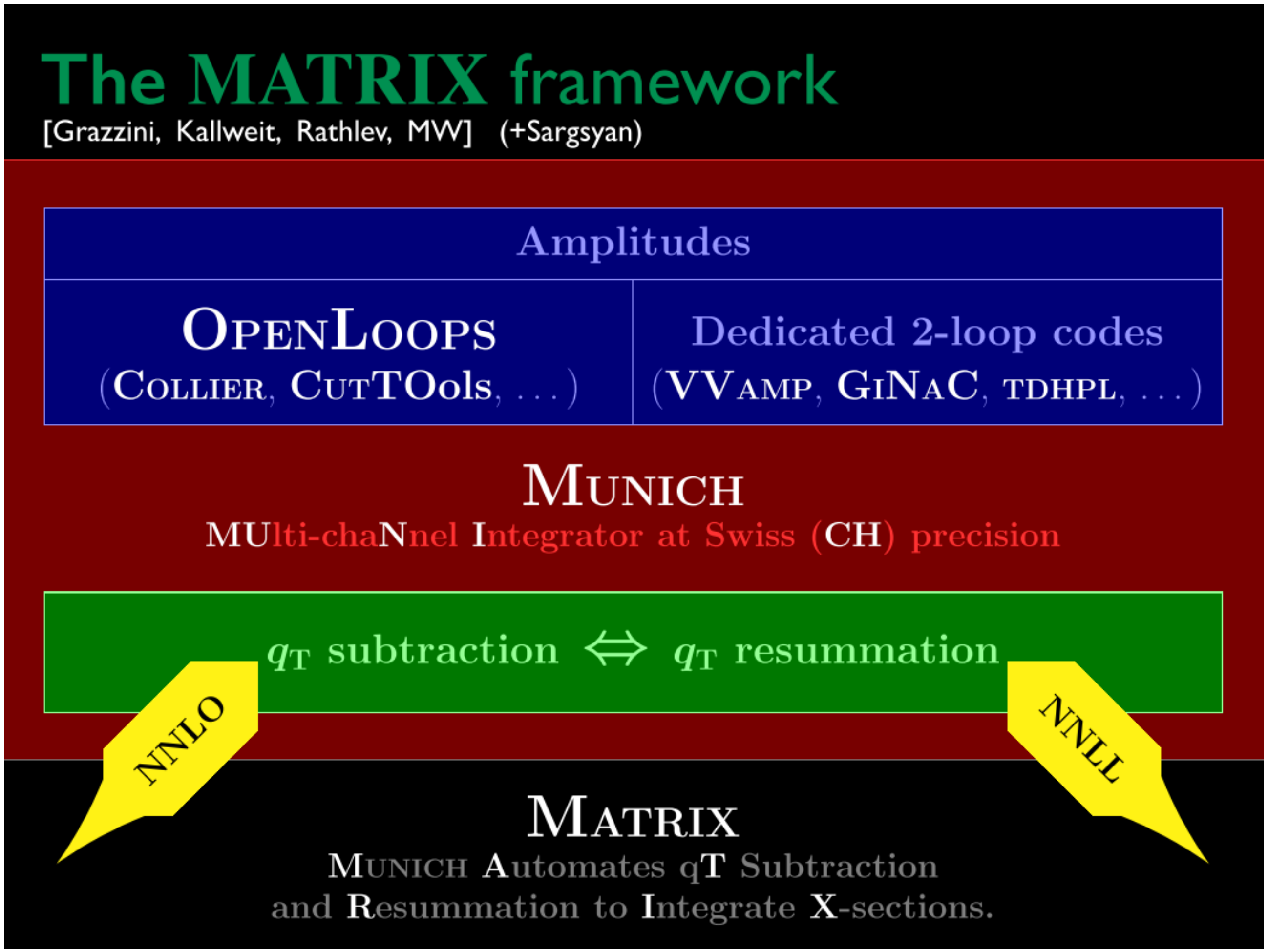
$$\mathrm{GF\ H(NNLO+m_t)} = \mathrm{Powheg}(1\,\mathrm{jet}\ m_t \to \infty) \times \frac{\mathrm{MG\ LO}\ 0-2\ \mathrm{jet}\ m_t}{\mathrm{Powheg}(1\,\mathrm{jet}\ m_t \to \infty)} \times \boxed{\frac{\mathrm{NLO}\ 1\,\mathrm{jet}\ m_t}{\mathrm{LO}\ 1\,\mathrm{jet}\ m_t}} \times \frac{\mathrm{NNLO}\ 1\,\mathrm{jet}\ m_t \to \infty}{\mathrm{NLO}\ 1\,\mathrm{jet}\ m_t \to \infty}\,.$$

CMS-PAS-HIG-17-010

- K-factors often taken from publications
- Computed in different phase spaces

NNLO predictions: the MATRIX example

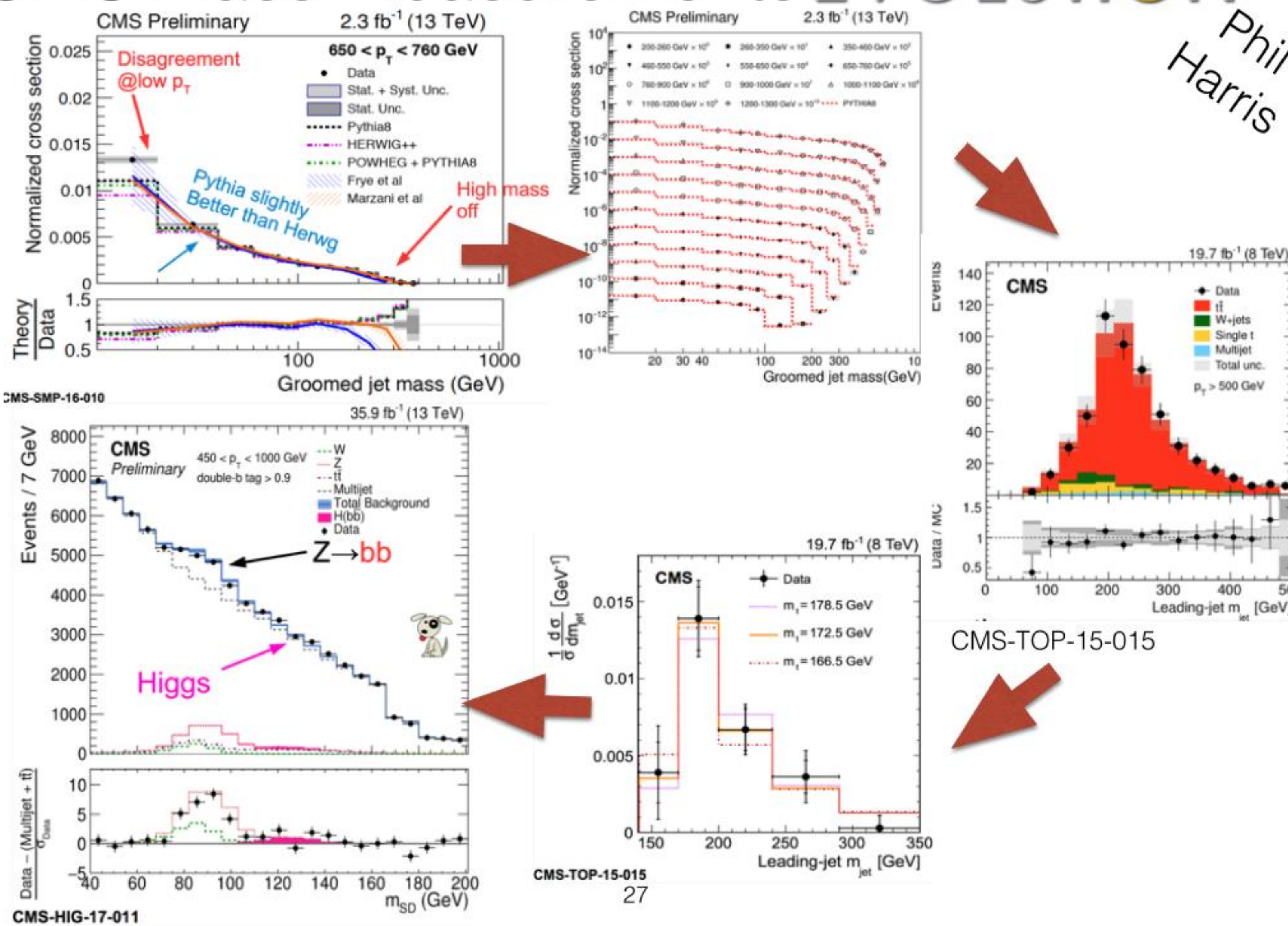
- Ambitious program to serve many use-cases



process	status
pp→Z/γ*(→ℓℓ/νν)	✓
pp→W(→ℓν)	(✓)
pp→H	✓
pp→γγ	✓
pp→Zγ→ℓℓγ	✓
pp→Zγ→ννγ	✓
pp→Wγ→ℓνγ	✓
pp→ZZ	✓
pp→ZZ→ℓℓℓℓ	✓
pp→ZZ→ℓℓℓ'ℓ'	✓
pp→ZZ→ℓℓν'ν'	✓
pp→ZZ/WW→ℓℓνν	✓
pp→WW	✓
pp→WW→ℓν ℓ'ν'	✓
pp→WZ	✓
pp→WZ→ℓνℓℓ	✓
pp→WZ→ℓ'ν'ℓℓ	✓
pp→HH	(✓)

A word on boosted techniques

- CMS mass measurements EVOLUTION



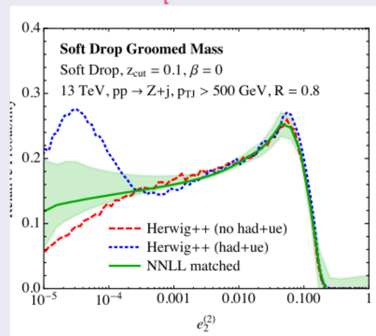
there would be no BOOST without...

- New Substructure Tools
  still new ideas after all those years
- New calculations
  now mainstream!
- Progress with pileup mitigation
  why shouldn't we use $R = 1$ after all?

No Boost without Calculations

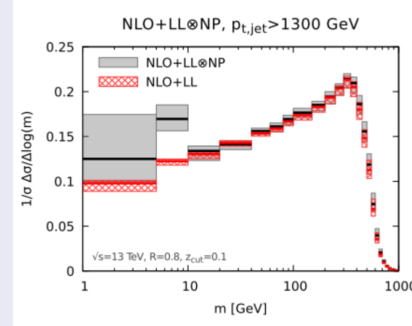
(N)LO+(N)NLL in SCET

[Andrew's talk in 2016]



NLO+(N)LL in "traditional" QCD

[Lais' talk]



Milestone for two reasons:

- we are entering into the precision-physics territory
- we start to address th uncertainties

Personal aside: Uncertainties

Question from BOOST 2014

"What is the uncertainty on the performance of our taggers?"

We start to be able to answer these questions

- Tools to make that possible: mMDT, SoftDrop, Recursive SoftDrop
- Existing calculations: groomed jet mass (NLO+(N)NLL)
- Possible calculations: Calculation and measurement is target for 2018
  - Groomed angularities, ...
  - Shapes: τ_{21}, D_2, possibly N_2 ((un)groomed or dichroic)
    should work at the LO+(N)LL accuracy. NLO probably possible
- Progress on uncertainties in Parton-Shower as well

We should be able to put a th uncertainty on ROC curves for tagger!

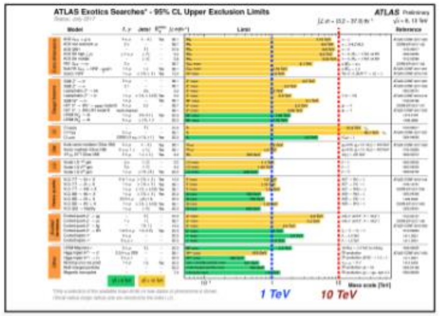
Personal aside: tentative NNLO timescale?

When will NNLO be relevant for substructure?

- we want $2 \to 3$ e.g. W/Z+jet or dijets
  (so as to have at least 2 particles in the jet!)
- $2 \to 2$ is availale
- rule of thumb adding one loop or one leg takes $\mathcal{O}(10)$ years

⇒ NNLO meets BOOST around 2025

- Note 1: large community effort so we may hope for better
- Note 2: Boost=small angles ⇒ delicate corner of phase space



Exotic / DM Searches

Higher √s and luminosity have greatly increased our reach for new physics up to high masses
Continuously developing new analysis techniques, exploiting more information

see talk by Jike Wang

Dijet

Dilepton

Diboson

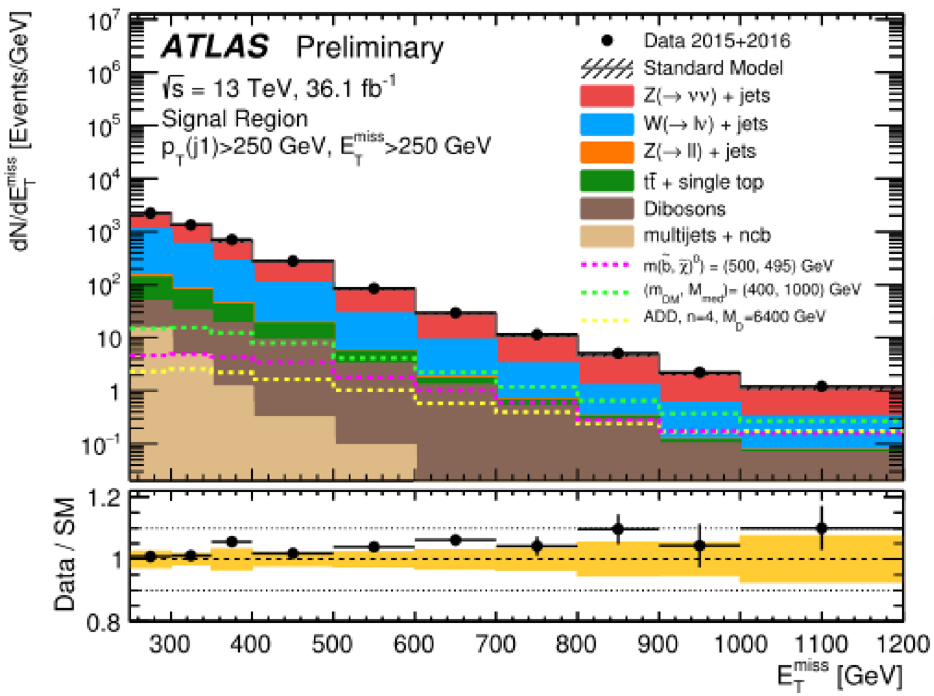
Vector Like Quarks

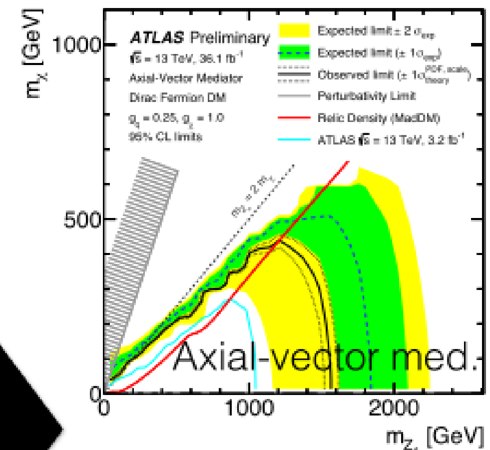
Dark Matter

Oliver Stelzer-Chilton, HEP18

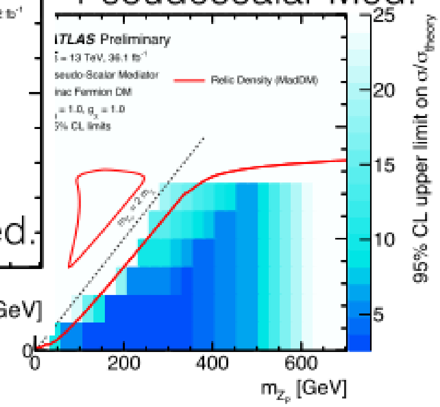
SM background in Monojet/MET+jets

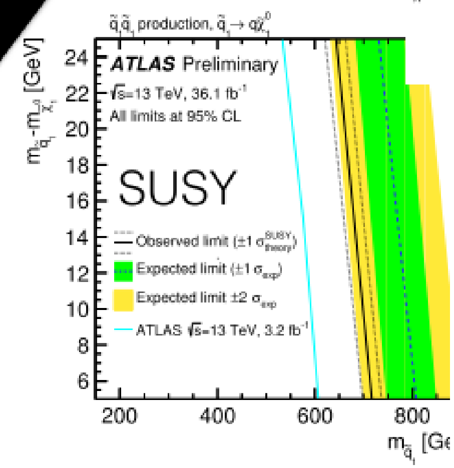
[ATLAS-CONF-2017-060]

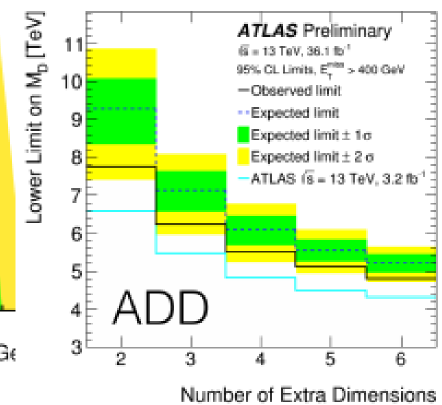




Pseudoscalar Med.







irreducible SM backgrounds:

pp→Z(→$\nu\bar{\nu}$)+jets ⟹ MET + jets

pp→W(→lν)+jets ⟹ MET + jets (lepton lost)

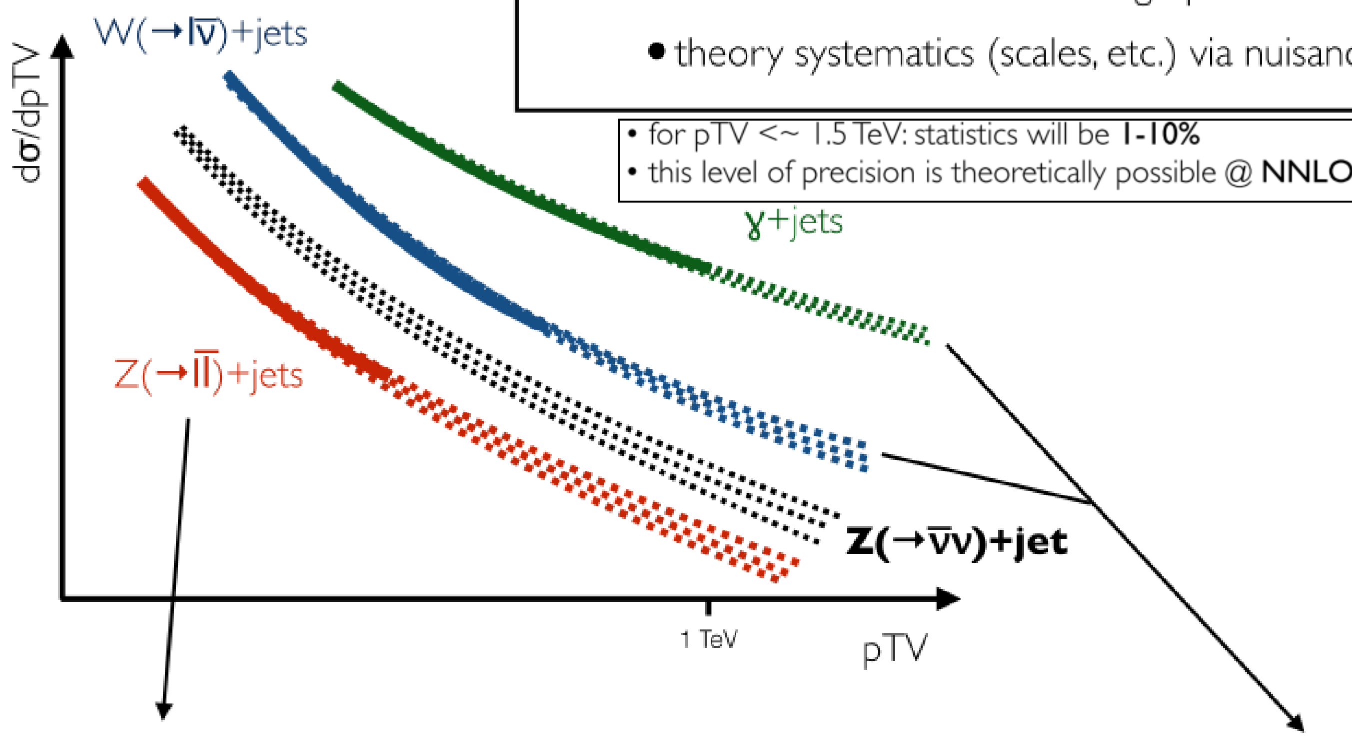
} V + jets

Determine V+jets backgrounds

global fit of Z(→ll̄)+jets, W(→lν̄)+jets and γ+jets measurements

- to determine Z(→ν̄ν)+jet
- and the visible channels at high-pT
- theory systematics (scales, etc.) via nuisance parameters in fit

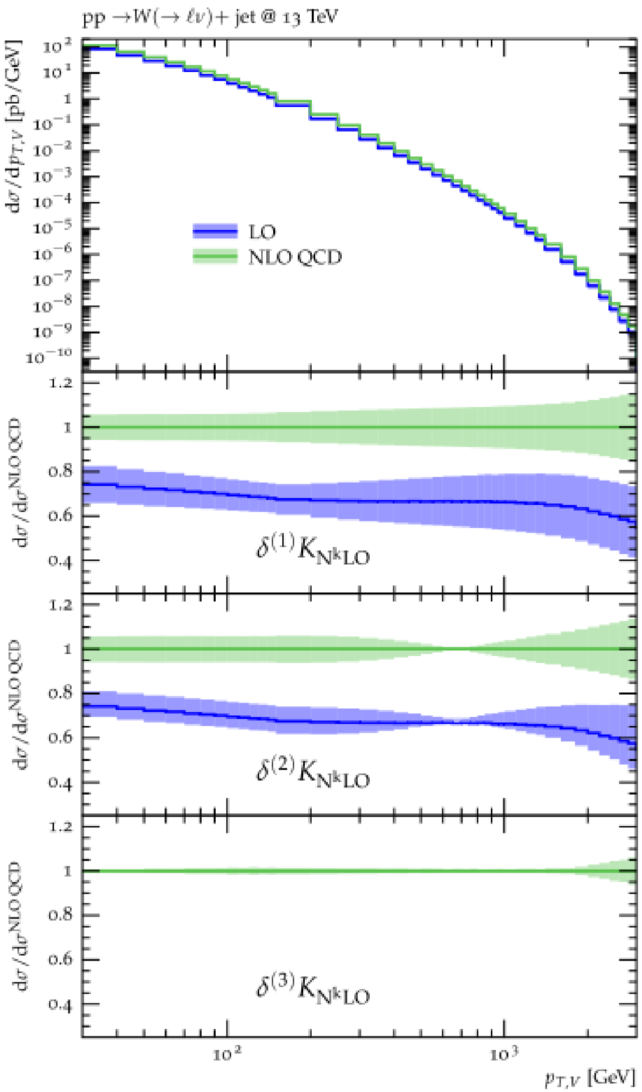
- for pTV <~ 1.5 TeV: statistics will be **1-10%**
- this level of precision is theoretically possible @ NNLO QCD + NNLO EW



- very precise at **low pT**
- hardly any systematics
- but: limited statistics at large pT

- fairly large data samples at **high pT**
- theoretical prediction required
- systematics from transfer factors

QCD uncertainties



$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{N^kLO\,QCD}}(\vec{\varepsilon}_{\mathrm{QCD}}) = \left[K^{(V)}_{\mathrm{N^kLO}}(x) + \sum_{i=1}^{3}\varepsilon_{\mathrm{QCD},i}\,\delta^{(i)}K^{(V)}_{\mathrm{N^kLO}}(x)\right] \times \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}}(\vec{\mu}_0).$$

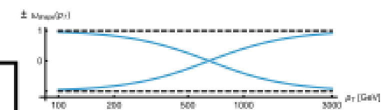
$$\epsilon^{(Z)}_{\mathrm{QCD,i}} = \epsilon^{(W^\pm)}_{\mathrm{QCD,i}} = \epsilon^{(\gamma)}_{\mathrm{QCD,i}} = \epsilon_{\mathrm{QCD,i}}$$

- correlated across processes
- correlated across pT bins

nuisance parameters:
interpreted as 1σ Gaussian

- $$\boxed{\delta^{(1)}K^{V}_{\mathrm{N^kLO}} = \frac{1}{2}\left[K^{V,\max}_{\mathrm{N^kLO}} - K^{V,\min}_{\mathrm{N^kLO}}\right]}$$ *(correlated)*

symmetrized **scale uncertainty**



- $$\boxed{\delta^{(2)}K^{V}_{\mathrm{N^kLO}} = \frac{p_{\mathrm{T}}^2 - 650\ \mathrm{GeV}}{p_{\mathrm{T}}^2 + 650\ \mathrm{GeV}}\delta^{(1)}K^{V}_{\mathrm{N^kLO}}}$$

yields max **shape distortion** within scale variation band *(correlated)*

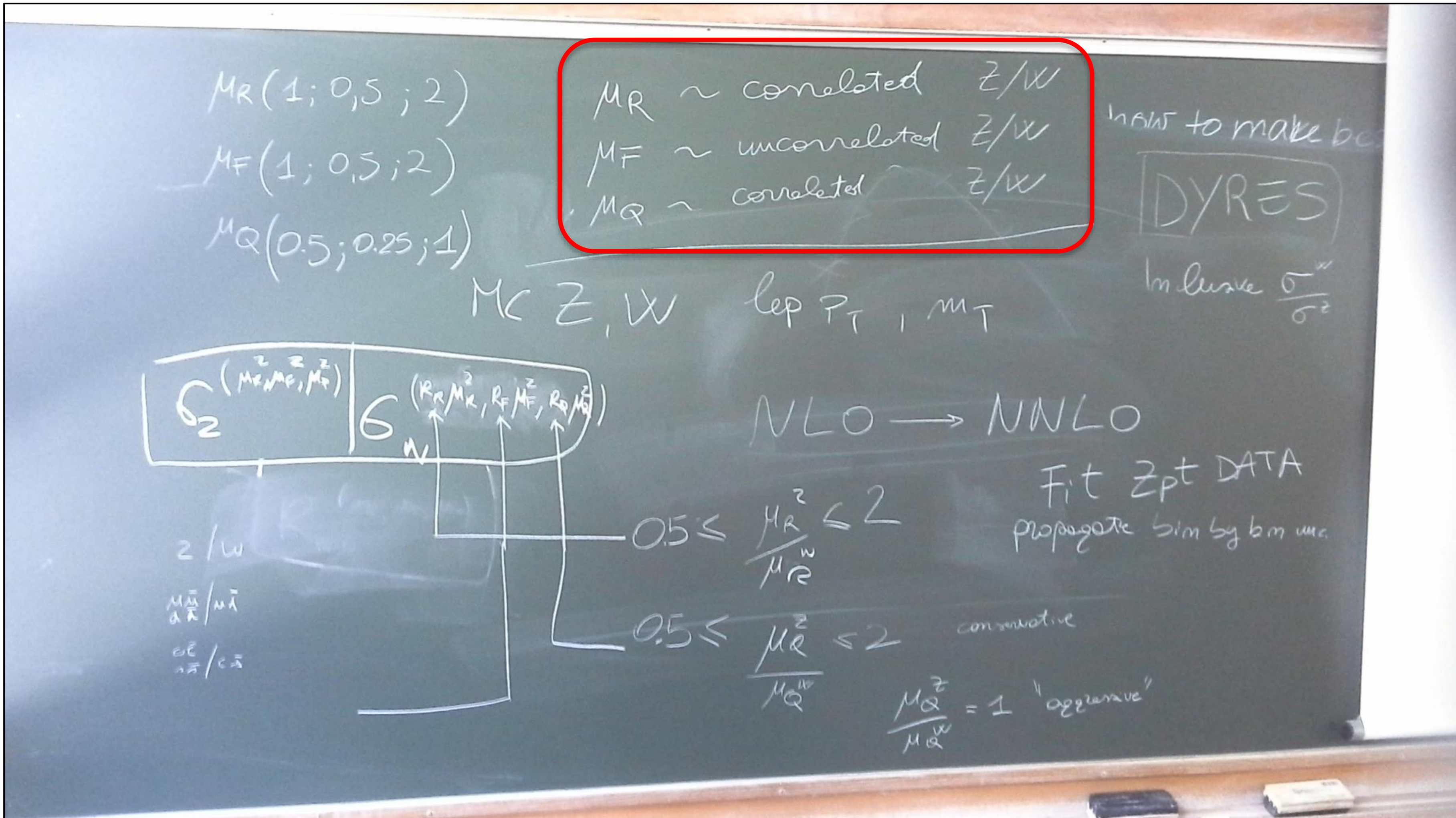
(important for extrapolation from low-pT to high-pT)

- $$\boxed{\delta^{(3)}K^{V}_{\mathrm{N^kLO}} = \frac{K^{V}_{\mathrm{N^kLO}}}{K^{V}_{\mathrm{N^{k-1}LO}}} - \frac{K^{Z}_{\mathrm{N^kLO}}}{K^{Z}_{\mathrm{N^{k-1}LO}}}}$$ *(correlated)*

Difference of (N)NLO corrections as **process correlation uncertainty**

About V+jets and scales…

- Back in Les Houches 2015
  - Suggestions on what to correlate for W mass…

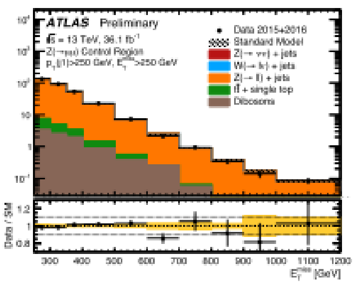


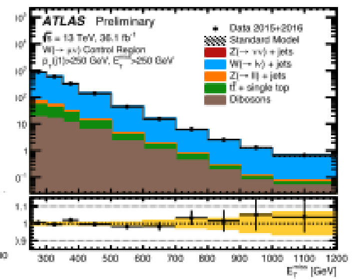
Experimental closure tests

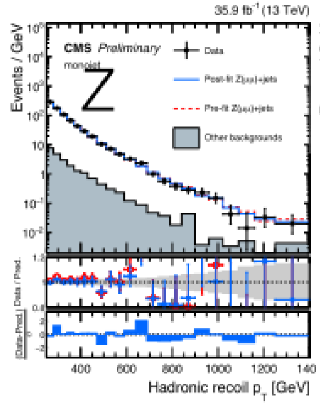
in recent ATLAS & CMS monojet searches

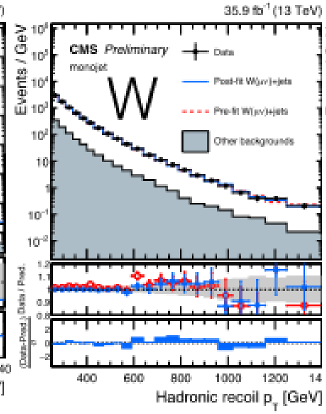
[ATLAS-CONF-2017-060] [CMS PAS EXO-16-048]

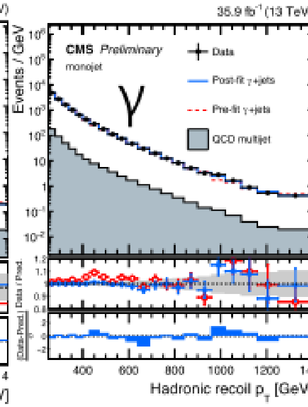
Nominals



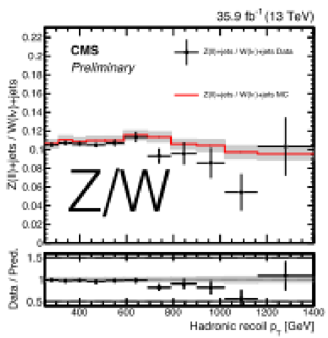


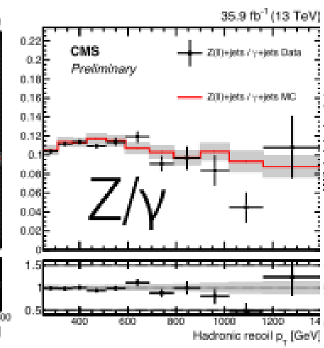


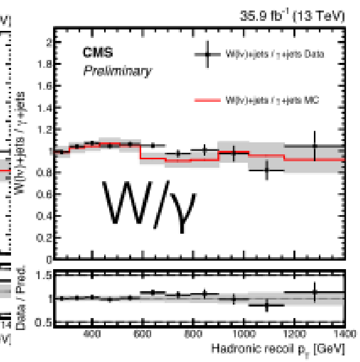




Ratios







It would be very nice to have this properly, i.e. as SM measurements!

Conclusions on V+jets rations and DM

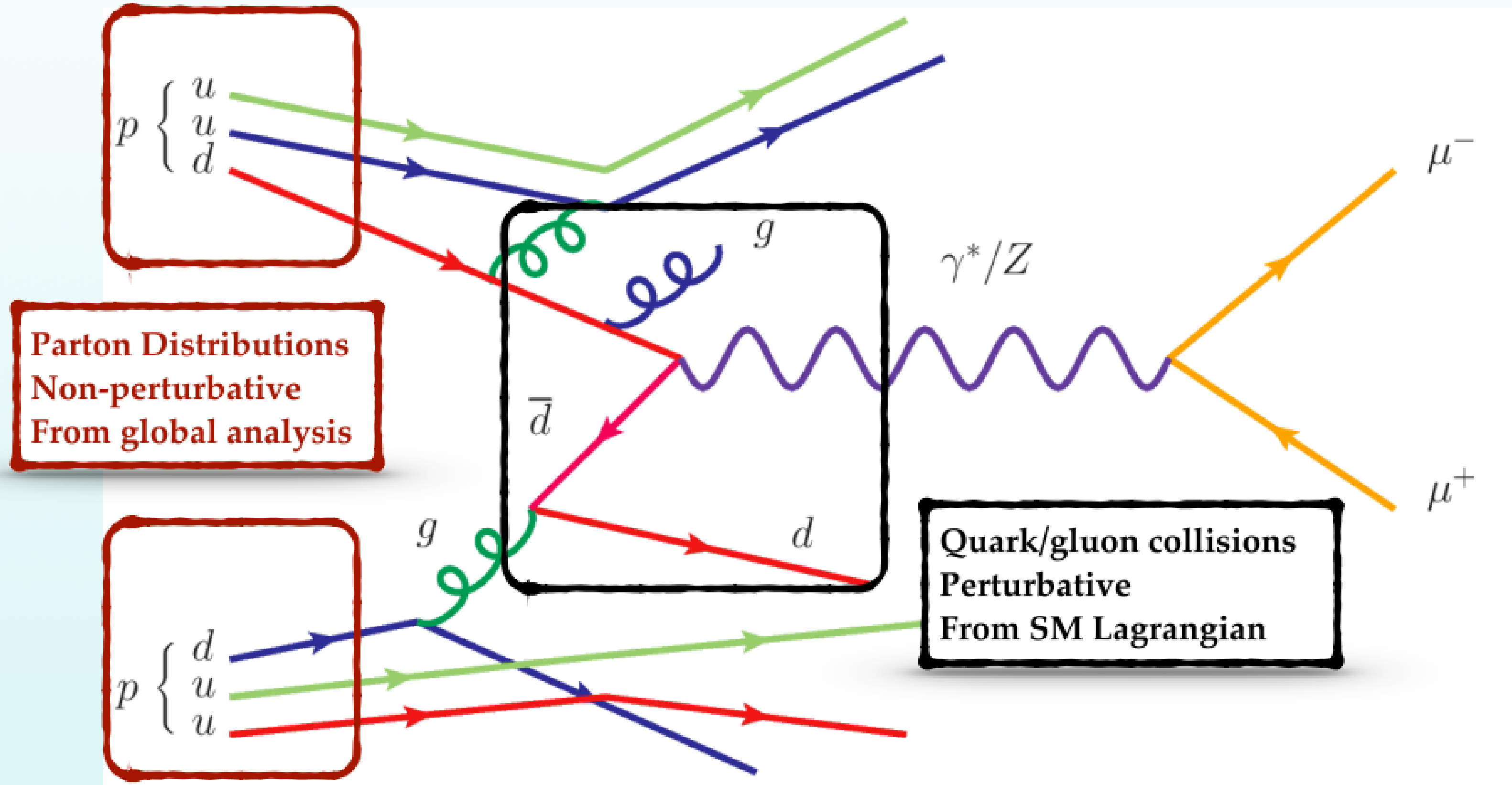
- at high energies inclusion of EW corrections *crucial* due to large Sudakov logs
- MC reweighting allows to promote V + jet to NNLO QCD+nNLO EW
- QCD, EW and QCD+EW perturbative systematics at large pTV under control at the level of 1-10%
- Control of V+jets backgrounds at this level of precision allows for unprecedented limits on DM production at the LHC

- Outlook: investigate many more DM search channels

Mono-Higgs	Mono-ɣ	leptons + MET	tt + MET
↓	↓	↓	↓
HV ratios	Zɣ / Vɣ ratios	VV ratios	ttV ratios

What else?

In high-energy **hadron colliders** the collisions involve **composite particles** (protons) with internal substructure (quarks and gluons): the LHC is actually a quark/gluon collider!



Calculations of **cross-sections** in hadron collisions require the combination of **perturbative cross-sections** with **non-perturbative parton distribution functions (PDFs)**

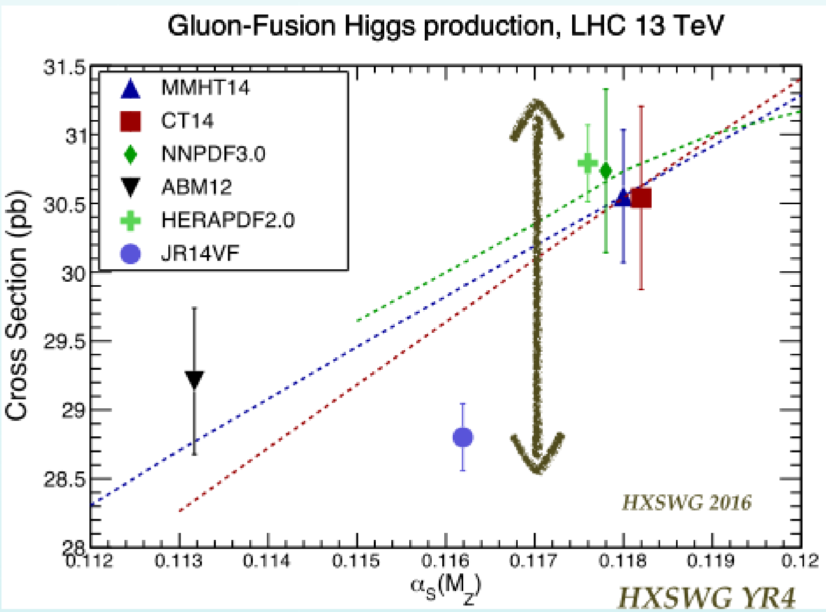
Why we need better PDFs?

Dominant TH unc for M_W measurements at LHC

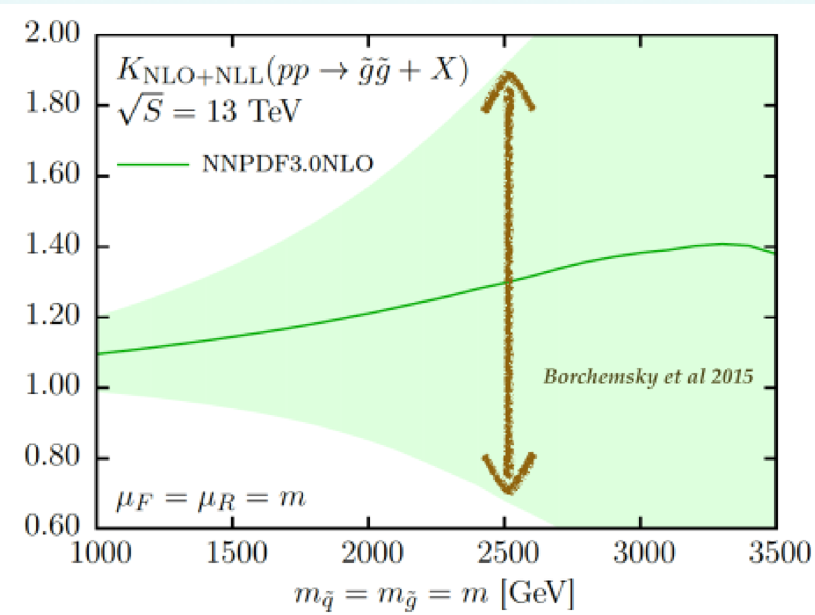
ATLAS 2017

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

Higgs coupling measurements



High-mass BSM cross-sections



PDF fits require a lot of data (and predictions!)

April 2017	NNPDF3.0	MMHT2014	CT14	HERAPDF2.0	CJ15	ABMP16
Fixed Target DIS	✔	✔	✔	✘	✔	✔
JLAB	✘	✘	✘	✘	✔	✘
HERA I+II	✔	✔	✔	✔	✔	✔
HERA jets	✘	✔	✘	✘	✘	✘
Fixed Target DY	✔	✔	✔	✘	✔	✔
Tevatron W,Z	✔	✔	✔	✘	✔	✔
Tevatron jets	✔	✔	✔	✘	✔	✘
LHC jets	✔	✔	✔	✘	✘	✘
LHC vector boson	✔	✔	✔	✘	✘	✔
LHC top	✔	✘	✘	✘	✘	✔
Stat. treatment	Monte Carlo	Hessian $\Delta\chi^2$ dynamical	Hessian $\Delta\chi^2$ dynamical	Hessian $\Delta\chi^2=1$	Hessian $\Delta\chi^2=1.645$	Hessian $\Delta\chi^2=1$
Parametrization	Neural Networks (259 pars)	Chebyshev (37 pars)	Bernstein (30-35 pars)	Polynomial (14 pars)	Polynomial (24 pars)	Polynomial (15 pars)
HQ scheme	FONLL	TR′	ACOT-χ	TR′	ACOT-χ	FFN (+BMST)
Order	NLO/NNLO	NLO/NNLO	NLO/NNLO	NLO/NNLO	NLO	NLO/NNLO

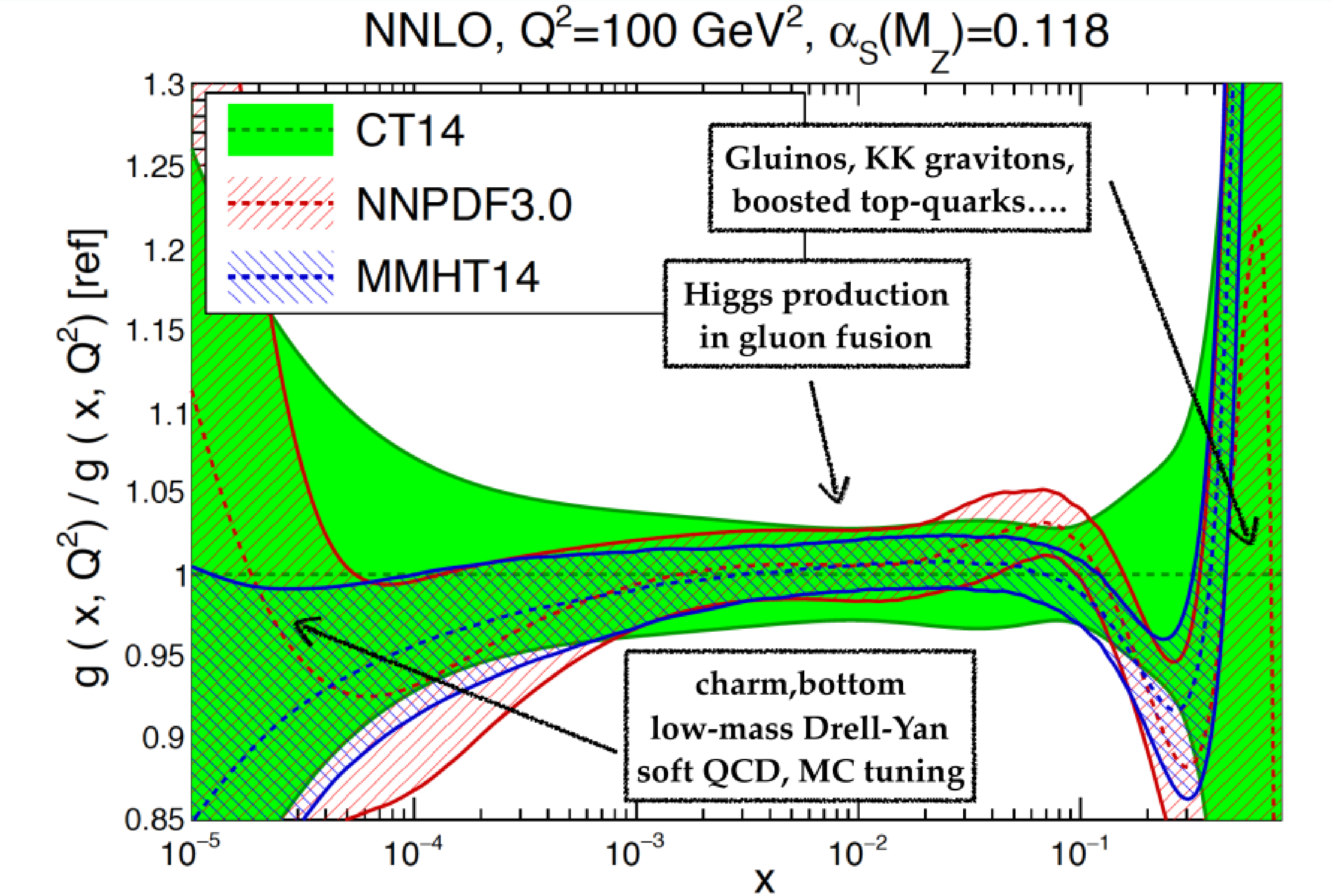
M. Ubiali, DIS 2017

NNPDF3.1 is the first NNPDF analysis where we find that **NNLO** gives a **markedly superior fit quality** as compared to **NLO**

Direct consequence of the **new high-precision measurements** included

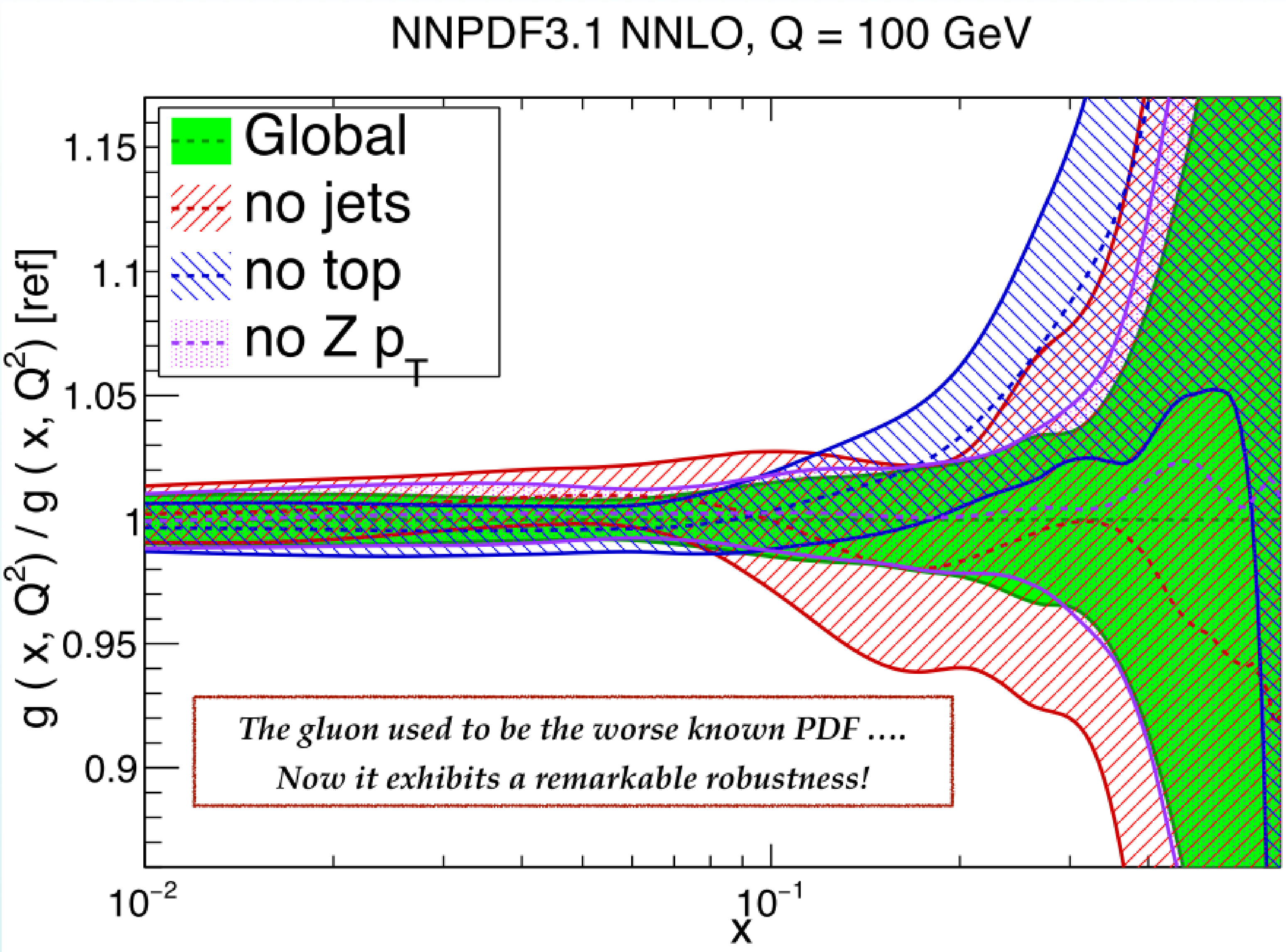
Strongly suggests that **NNLO PDFs should be the baseline** in all analyses!

One glue to bind them all

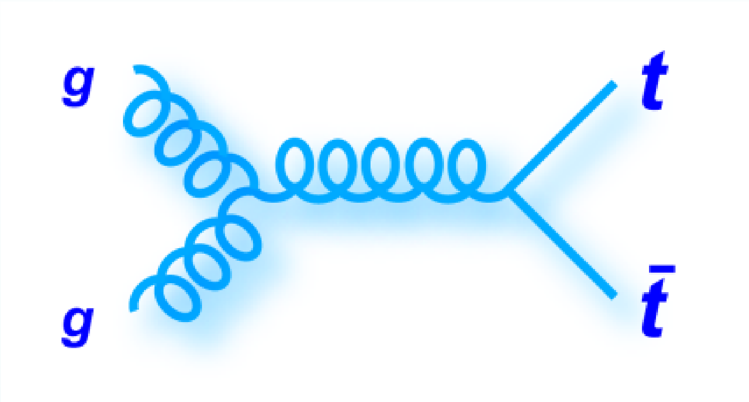


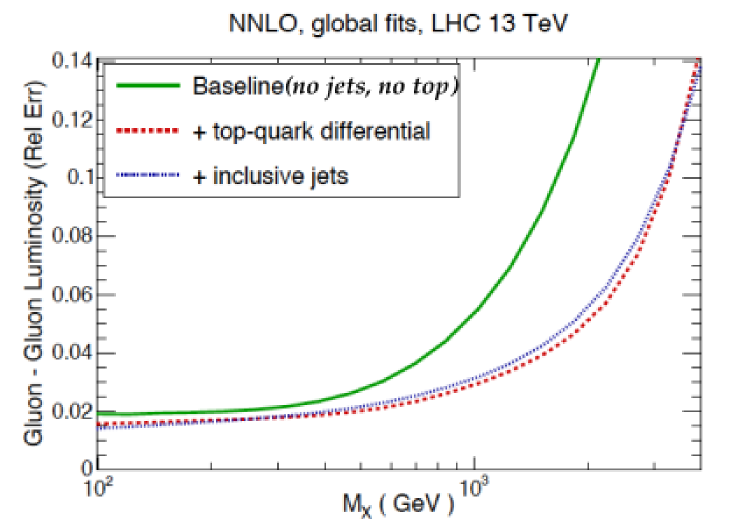
At the LHC, precise knowledge of the gluon is required **from small-x to large-x**

One (upgraded) glue to bind them all

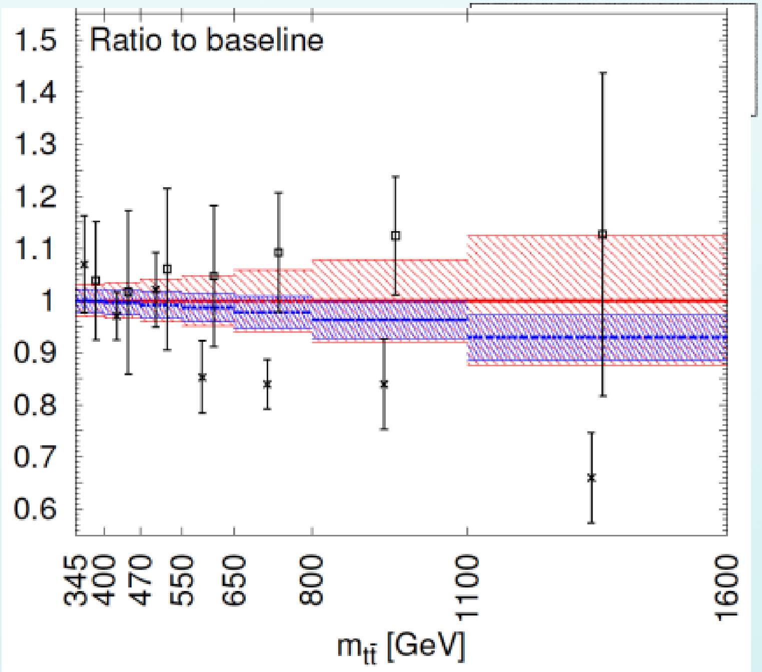


The large-x gluon from differential top quarks

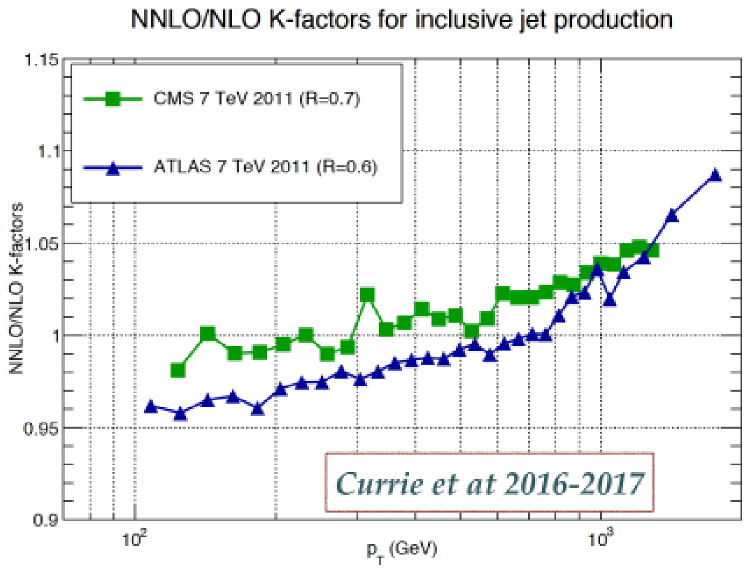




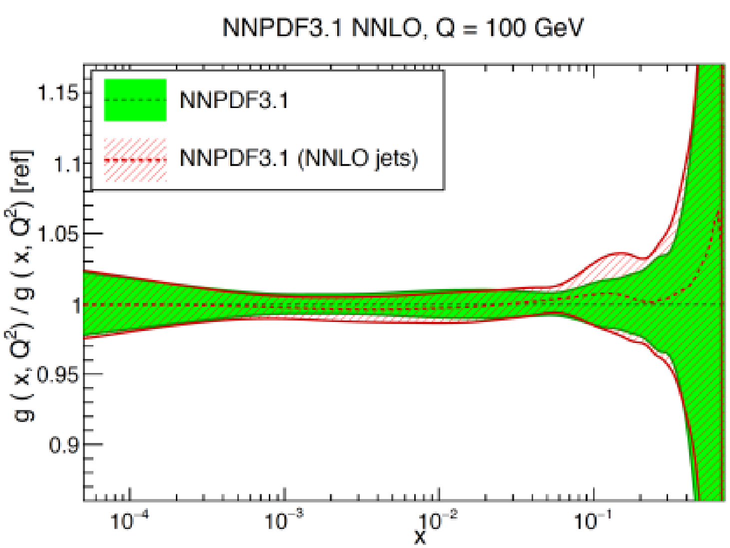
- Top-quark production driven by **gluon-gluon scattering**
- **NNLO calculations for stable top quarks** available *Czakon, Mitov et al 2015-2017*
- **Data from ATLAS and CMS at 8 TeV** available with breakdown of systematic uncertainties
- Included **differential top data into NNPDF3.0**: constraints on the **large-*x* gluon** comparable to those of inclusive jet production *Czakon et al 2017*
- Improved theory uncertainties in **regions crucial for BSM searches**, *i.e.*, $\mathbf{m_{tt} > 1}$ **TeV** (while fitting only $\mathbf{y_t}$ and $\mathbf{y_{tt}}$)



The large-x gluon from NNLO jets



- NNPDF3.1 NNLO: includes jet data using **NNLO evolution and NLO matrix elements**, with scale variations as additional TH systematic error
- The **jet p_T** is always used as central scale choice
- Also tried variants where ATLAS and CMS 2011 7 TeV data included **using exact NNLO theory**
- Very small impact on the gluon
- Moderate improvement of the chi2
- *Only central bin of ATLAS data included - the large χ^2 once all bins are included remains there once exact NNLO theory is used*



	NNPDF3.1	exact NNLO
CDF Run II k_t jets	0.84	0.85
ATLAS jets 2.76 TeV	1.05	1.03
CMS jets 2.76 TeV	1.04	1.02
ATLAS jets 2010 7 TeV	0.96	0.95
ATLAS jets 2011 7 TeV	1.06	0.91
CMS jets 7 TeV 2011 7 TeV	0.84	0.79

See also MMHT analysis, Harland-Lang et at 16

How bright is the proton?

- The calculation of **QED and electroweak corrections to hadron collider processes** requires by consistency to introduce the PDF of the photon in the proton, **$\gamma(x,Q)$**
- The first model-independent determination of **$\gamma(x,Q)$** from LHC *W,Z* data was **NNPDF2.3QED**, which however affected by **large uncertainties**, due to the limited experimental information
- Recently, **$\gamma(x,Q)$ computed** in terms of the well-known **inclusive structure functions F_2 and F_L**: the resulting photon PDF, exhibits now **few-percent uncertainties**

$$x\gamma(x,\mu) = \frac{1}{2\pi\alpha(\mu)} \int_x^1 \frac{dz}{z} \left\{ \int_{Q^2_{\rm min}}^{\mu^2/(1-z)} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \left[-z^2 F_L(x/z,Q^2) + \left(zP_{\gamma q}(z) + \frac{2x^2m_p^2}{Q^2} \right) F_2(x/z,Q^2) \right] - \alpha^2(\mu) z^2 F_2(x/z,\mu^2) \right\} + \mathcal{O}\left(\alpha\alpha_s, \alpha^2\right)$$

Manohar, Nason, Salam, Zanderighi, 16-17

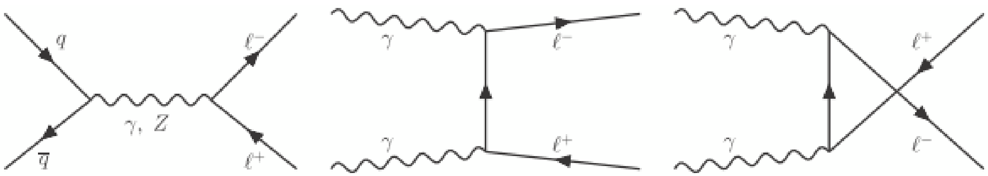
pp → H W⁺ (→ l⁺ν) + X at 13 TeV	
non-photon induced contributions	91.2 ± 1.8 fb
photon-induced contribs (NNPDF23)	$6.0^{+4.4}_{-2.9}$ fb
photon-induced contribs (LUXqed)	4.4 ± 0.1 fb

Crucial implications for LHC pheno: high-precision determination of photon-initiated (PI) contributions

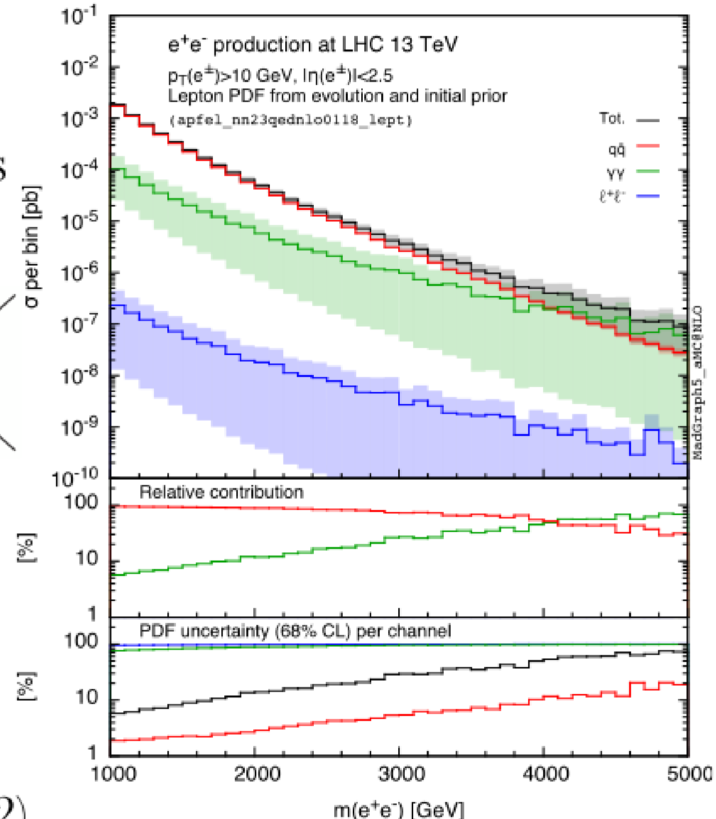
Photon PDF and BSM

Motivation

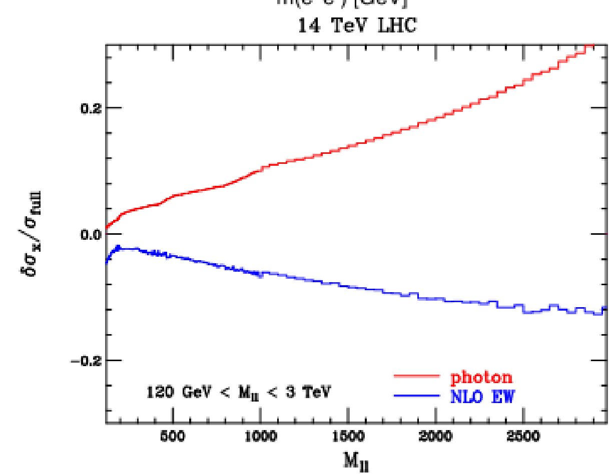
- The **Drell-Yan** process (pp→l^+l^-) receives photon-initiated contributions at LO:



- **High-invariant-mass** region gets large photon contribution:
  - up to the same order or even larger than the QCD contribution.
  - probe the **large-*x* photon PDF** ($x \gtrsim 0.02$).
- Experimental data in this region can provide a constraint on the **photon PDF**:
  - ATLAS high-mass DY data.
    [G.Aad et al., JHEP 08 , 009 (2016)]
- Need for accurate predictions: **QED/EW corrections to NLO**.



[V. Bertone et al., JHEP11(2015)194]



[R. Boughezal et al., P. R. D 89 (2014)]

Aren’t we forgetting anything?

Biasing/binning

- *Generating enough MC for the expected dataset is a tremendous challenge! (+more for systematics)*

Most of systematics (ME+PS) now dealt with through weights! But it takes time to educate the community…

- critical for the future to have better generator filters to keep up with the larger and larger dataset.
  - "**better**" means **faster** (applied earlier on) and more **flexible** (include various observables)
- Slicing vs biasing all @ NLO - which will give more stable results
- NB: *negative weights* or *large event weights* **are killer** when limited MC stats are available

Data → Theory link

- probably the most challenging problem to solve – **the inverse problem of decoding of the underlying theory from signal**
  - requires database of models, database of signatures
  - requires smart procedure based on machine learning of matching signal from data with the pattern of the signal from data

- **HEPMDB (High Energy Physics Model Database)** was created in 2011 **hepmdb.soton.ac.uk**
  - convenient centralized storage environment for HEP models
  - it allows to evaluate the LHC predictions and perform event generation using CalcHEP, Madgraph for any model stored in the database
  - you can upload their own model and perform simulation

- As a HEPMDB spin-off the **PhenoData** project was created **hepmdb.soton.ac.uk/phenodata**
  - stores data (digitized curves from figures, tables etc) from those HEP papers which did not provide data in arXiv or HEPData
  - has an easy search interface and paper identification via arXiv, DOI or preprint numbers

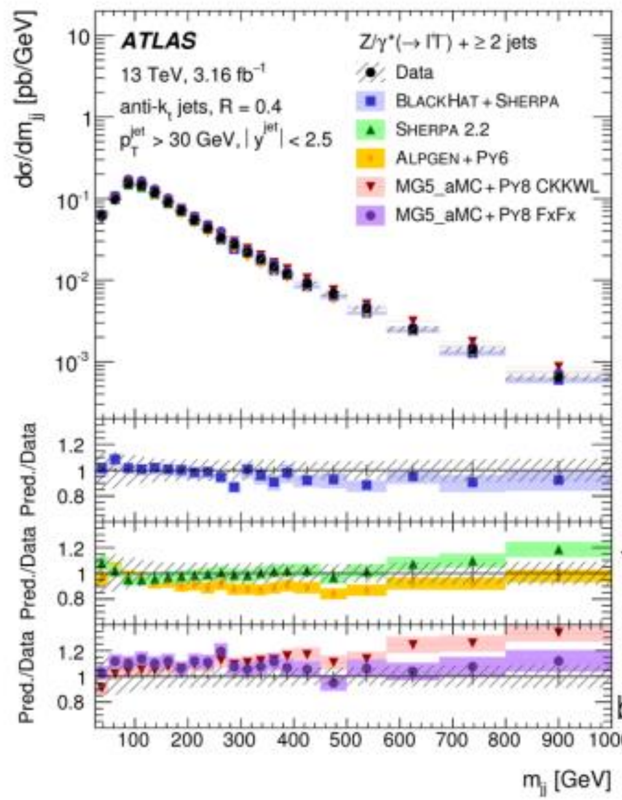
More Than Limits

- Search groups burn through the data much faster than measurement groups

(Think search control regions not signal regions)

(Not discussing re-interpretation)

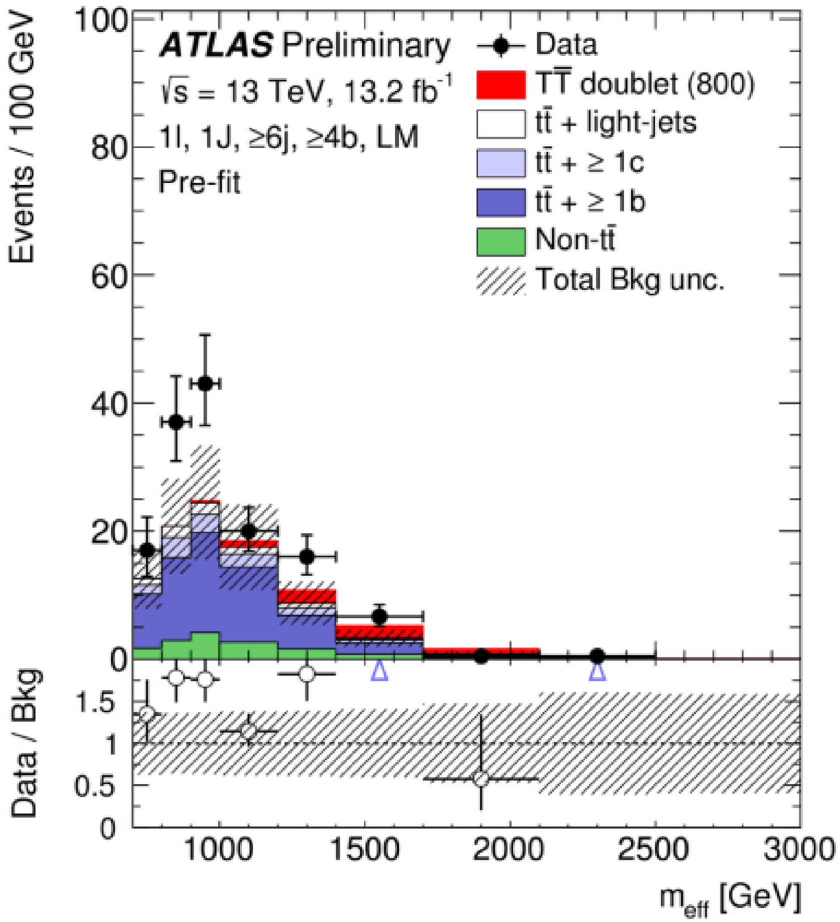
- ***Can searches provide more useful information for MC generator tuning?***
  - Living in the *extremes of phase* space where measurements are less likely to be.
  - What is the **minimal** amount of information?
  - Will you *use it*? Don't just say "yes"!

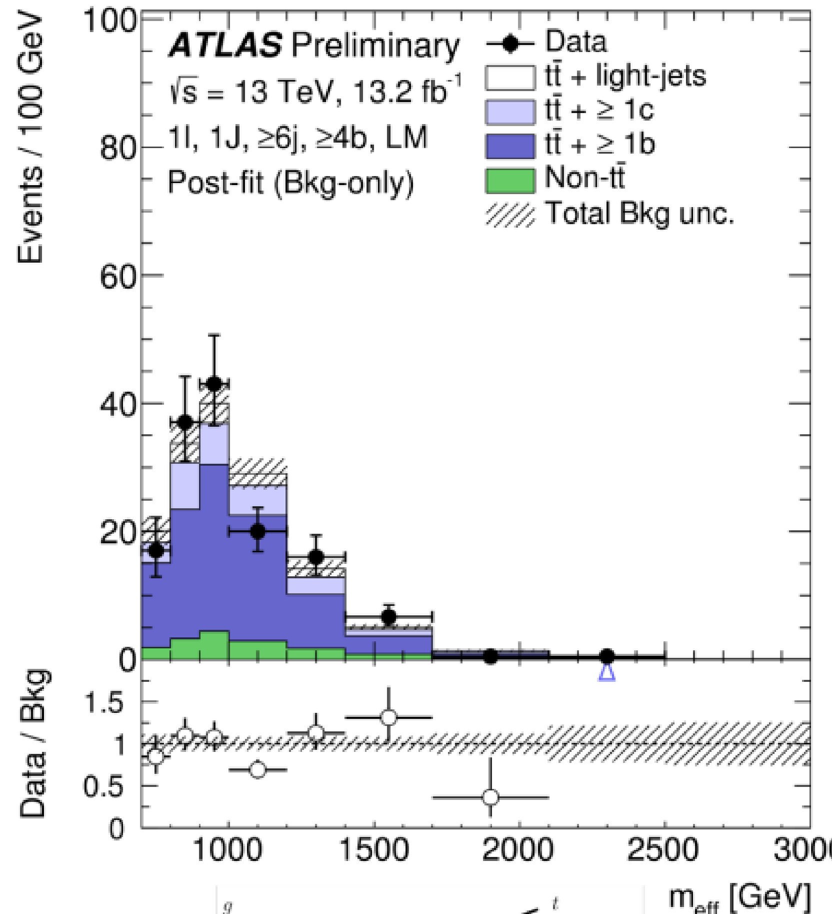


guess what happens beyond 1 TeV!

arXiv:1702.05725

More Than Limits





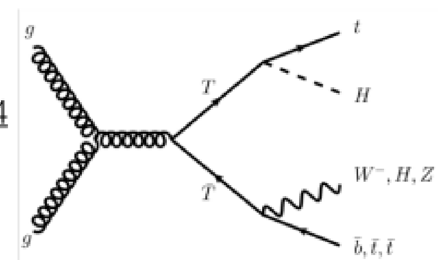
At all useful?

tt: Powheg v2 + Pythia 6, CT10 PDF set

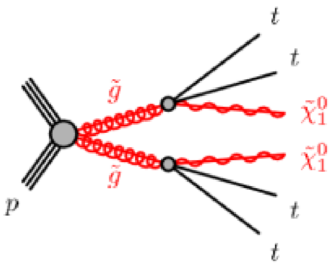
MET (W), MET+m_T^W, 1 leptons, 5+ jets, 2+ b-jets

ATLAS-CONF-2016-104

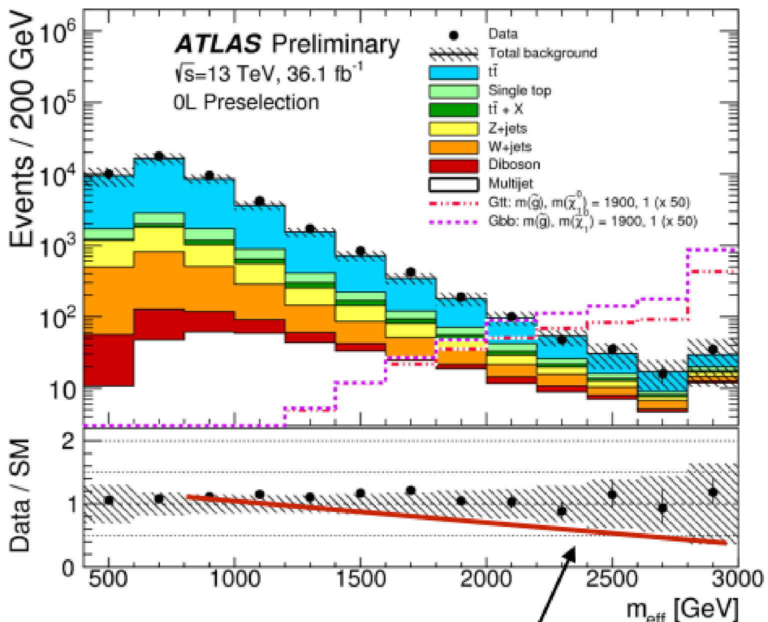
14



More Than Limits

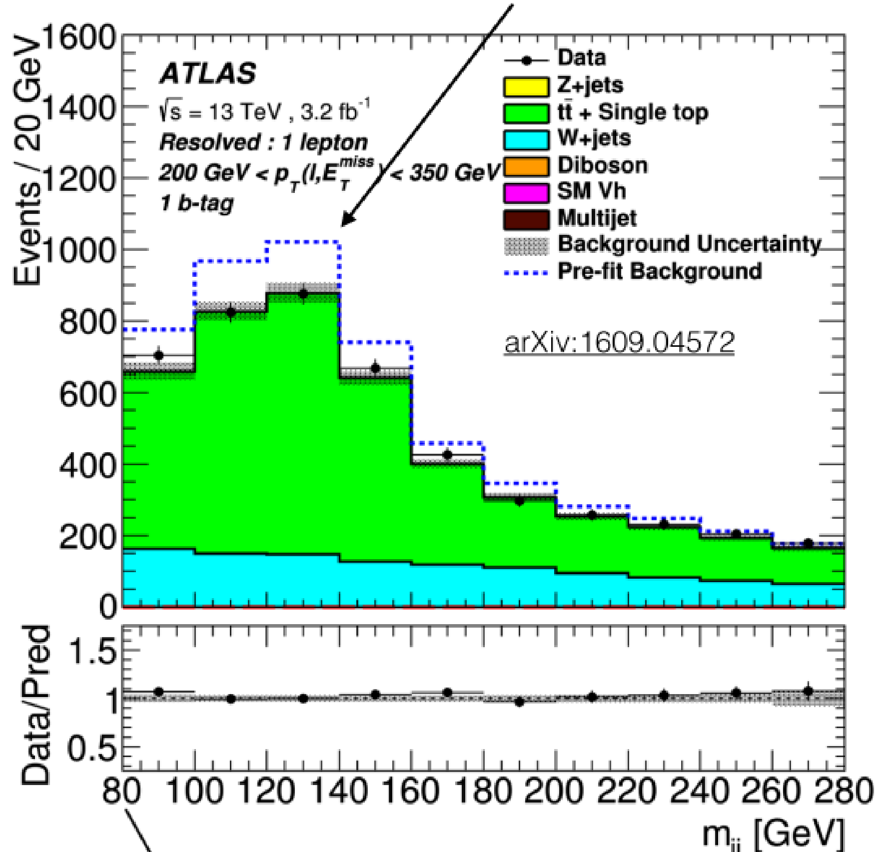


ATLAS-CONF-2017-021



what if we showed you this?

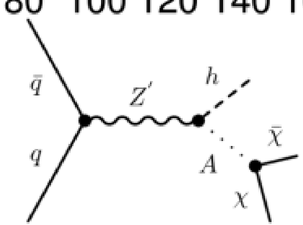
At all useful?



tt: Powheg v2 + Pythia 6, CT10 PDF set

MET, 0 leptons, 4+ jets, 2+ b-jets, $\Delta\Phi$(jets)>0.4

15



W pT cut, 1 lepton, 2 jets, 1 b-jets, anti-QCD cuts, H_T

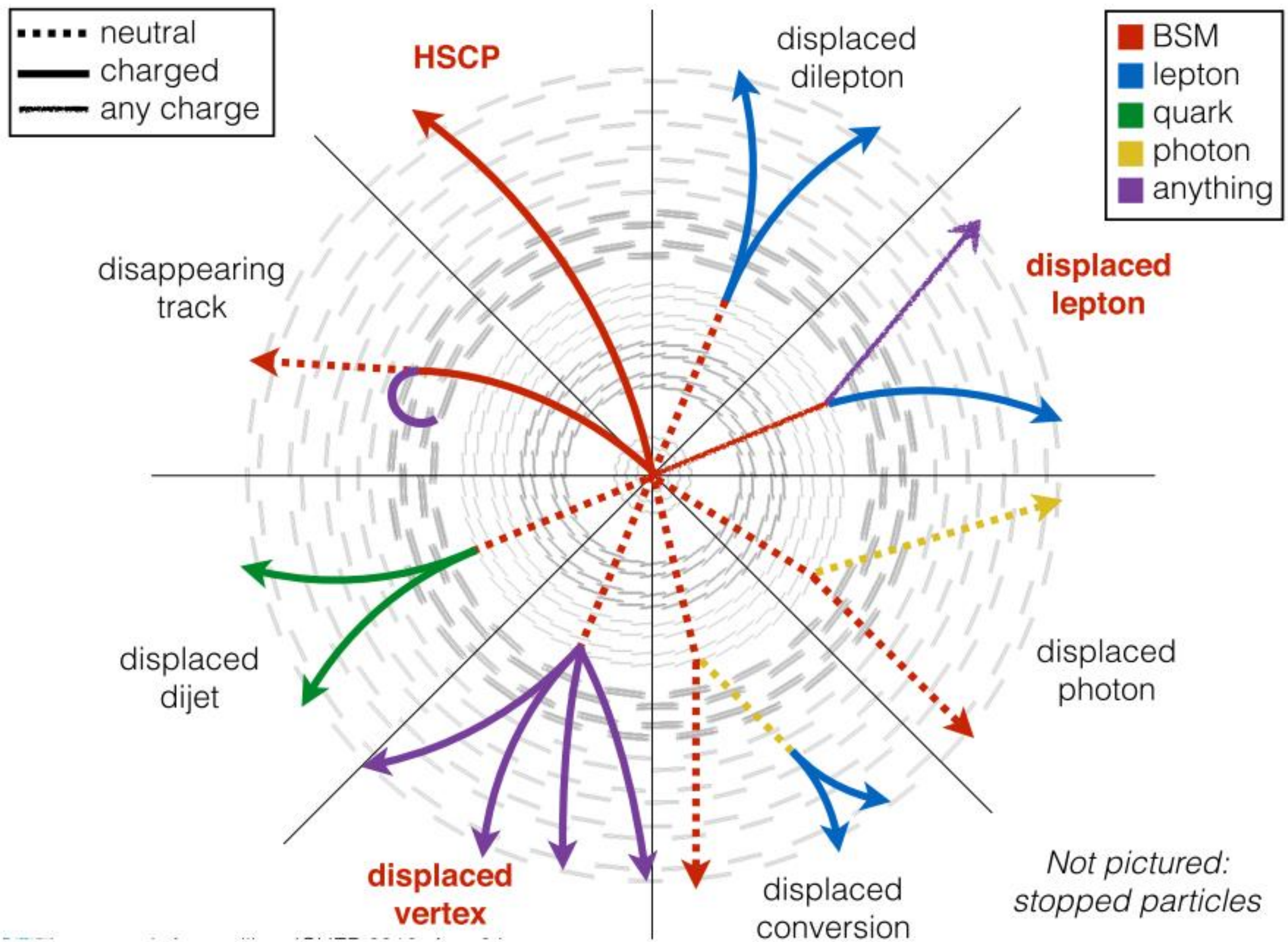
More Than Limits

- How to compare currently **non-unfolded distributions** to new MC version outside of experimental collaborations?
  - We often reweigh or only show "post-fit" MC.
    If given MC before this, would it be useful?
  - Is **folding i.e. via Rivet routines** a viable option?
- What *regions of phase space near where searches are being done* are interesting to measure in order to understand MC better?
  - If you had **one wish**, it would be to see a plot of…
- To what *extent is it important to unfold distributions* in order for generator authors to improve MC?

Concluding remarks

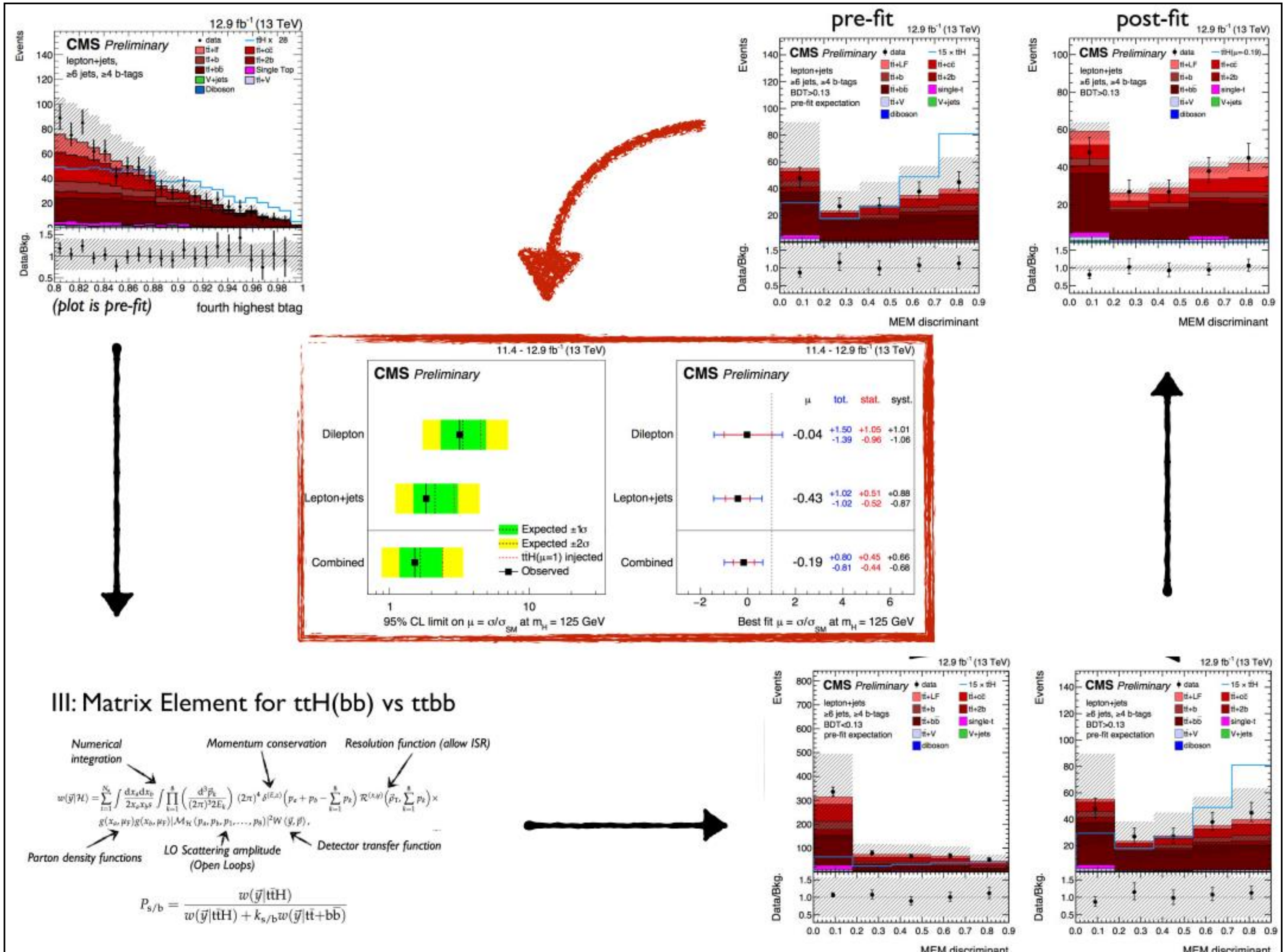
My worst nightmare

J. Antonelli

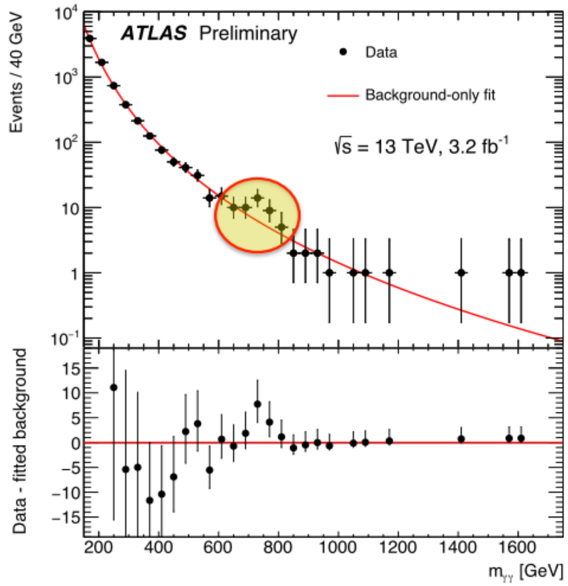


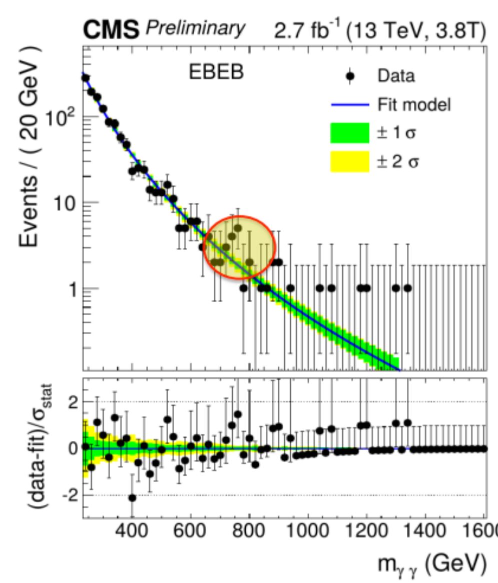
Theorists' worst nightmare: discriminators

" […] benefit from a bit more transparency in the elucidation of the actual underlying dynamics, e.g. seeing data vs MC comparisons for more intuitive observables […] "



(Very) Provocative question





- How much advancement in QCD would have been possible **if**:
  - At least 50% of the work to produce O(500+) papers to justify (a posteriori) the diphoton excess at 750 GeV would have focused instead on INCREASING THE PRECISION of the SM BACKGROUND MODEL ? ☺
- Of course, a lot of arguments apply (including sociological ones)
  - But we need to ask ourselves these questions
  - And find a way to reward, job-wise, “precise and boring” calculations more (better, other) than only newer and newer models
  - Otherwise, what are we discussing about?

Answer: likely 0

Writing quick paper to justify a new model is easy, to make a new SM calculation can take forever…

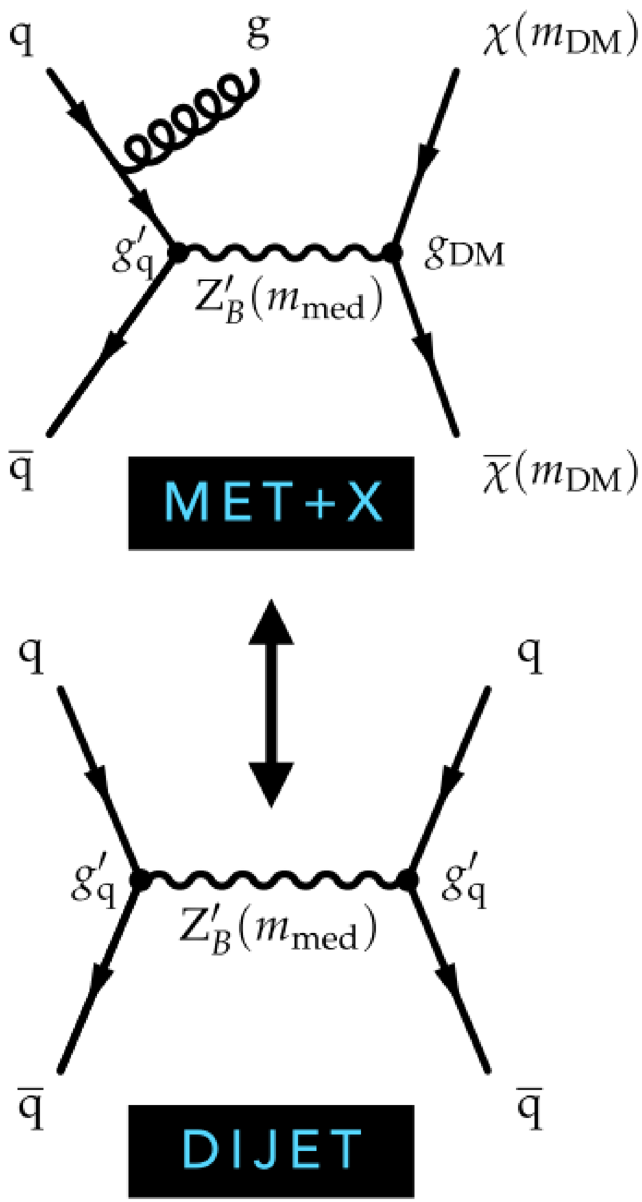
Conclusions

- Continue working on SM measurements and predictions
  - They will become useful for BSM searches
    - Soon or later
      - But they will

- While waiting for the big BSM fish…

Backup

Simplified DM models guidance



Typical signatures at the LHC:

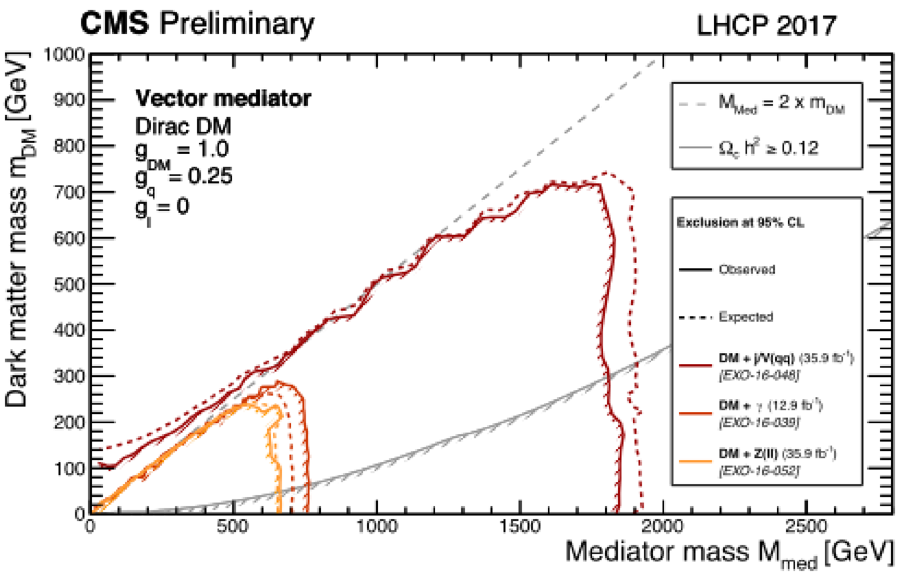
- mono-X (X = jet, photon, W, Z, H, t)
  - jet: generally the most powerful
  - photon: first used for the DM searches
  - W: distinguish DM coupling to u/d-quarks
  - Z: clean signature
  - H: Higgs portal
  - t: coupling to tops
- di-X resonance (X = jet, photon, W, Z, H, t)
  - X = jet is naturally connected with the DM@LHC
  - others are more model-dependent

4D parameter space: g_{DM}, g_q, m_{DM}, m_{med}:

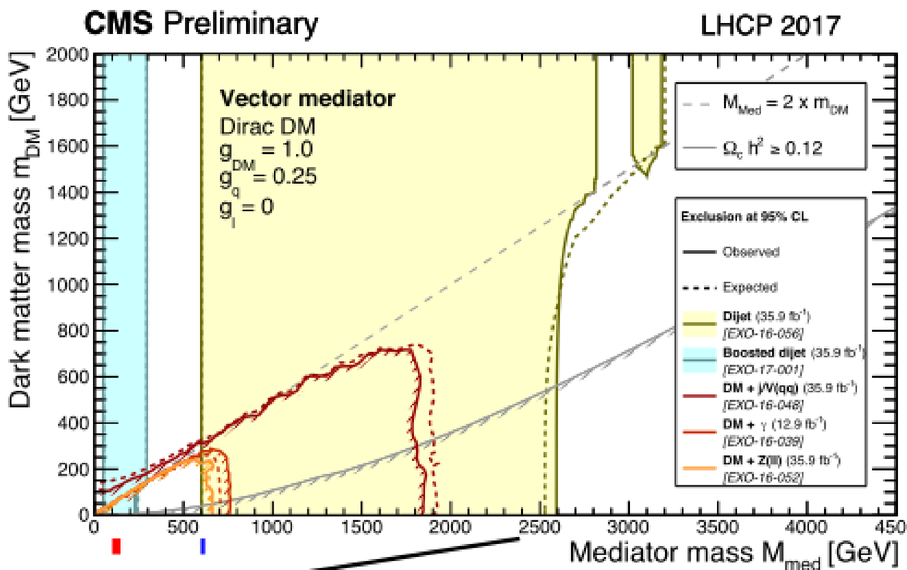
- m_{DM}, m_{med} pushed by energy rise
- g_{DM}, g_q require luminosity

Results complementarity

mono-X + E_T^{miss} searches:



+ dijet resonance searches



limited by $\sqrt{s}$

limited by trigger

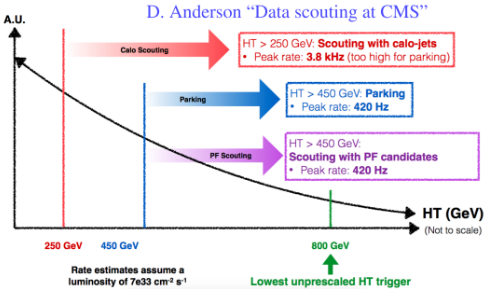
new ideas and techniques to cover the gaps

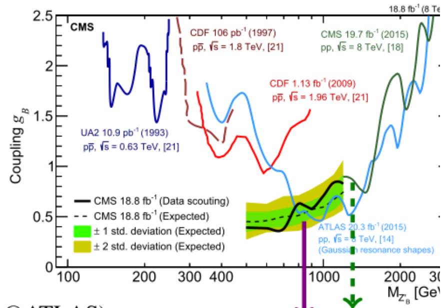
CMS-PAS-EXO-16-056

Overcoming high trigger rates

An approach already tested in Run 1: store only objects reconstructed with trigger

D. Anderson "Data scouting at CMS"





usual HT trigger

PF scouting result

Data scouting concept (*Trigger-level analysis*@ATLAS):

- physics objects are reconstructed online
- the HLT objects are saved in a minimal format
- no additional offline reconstruction

Reduce event size from 500 kB/event to

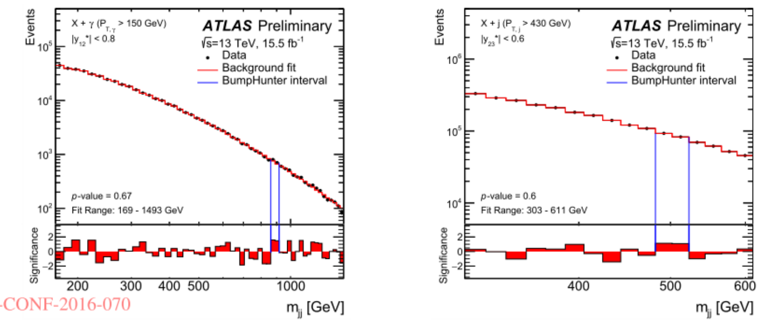
- 10 kB/event: PF scouting, $H_{\mathrm{T}} > 450$ GeV (CPU-limited)
- in Run 2: 1.5 kB/event: Calo scouting, $H_{\mathrm{T}} > 250$ GeV

arXiv:1604.08907

New ideas: employing ISR to go lower...

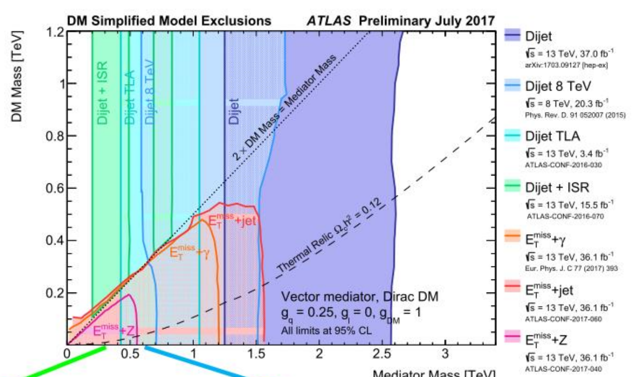
Sacrifice in coupling sensitivity to go lower in mass:
trigger on initial-state radiation (jet or photon) and search for recoiling dijets

- ISR γ threshold: $E_{\mathrm{T}} > 150$ GeV
- ISR jet threshold: $E_{\mathrm{T}} > 430$ GeV



ATLAS-CONF-2016-070

Closing the gaps: ATLAS searches



Dijet + ISR:

- γ ISR: masses between 200 and 1000 GeV
- jet ISR: masses between 450 and 1000 GeV

Trigger-level analysis (**Dijet TLA**):

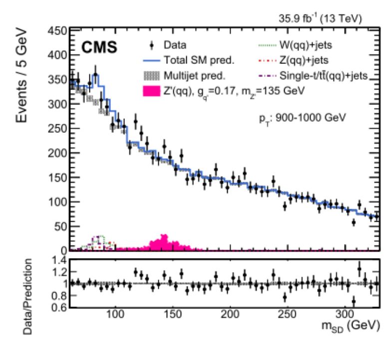
- masses between 450 and 1100 GeV

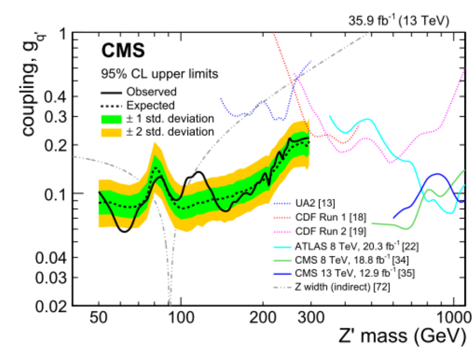
ATLAS-CONF-2016-070 ATLAS-CONF-2016-030

Going below 200 GeV: CMS ISR+merged jet search

Going even lower in mass: dijets start to merge into one jet with substructure

- exploring masses between 50 and 300 GeV
- a challenge: simple bump-hunt does not work anymore (SM Z boson is in the range)
- use "fail" substructure variable sideband to estimate SM bkg shape and yield

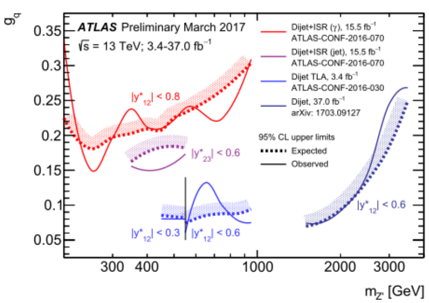


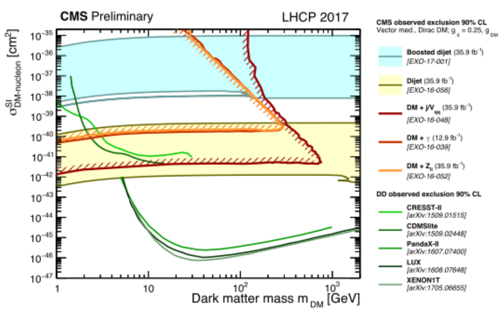


Local (global) significance 2.9σ (2.2σ) at 115 GeV

arXiv:1710.00159

Remembering about other dimensions: g_q



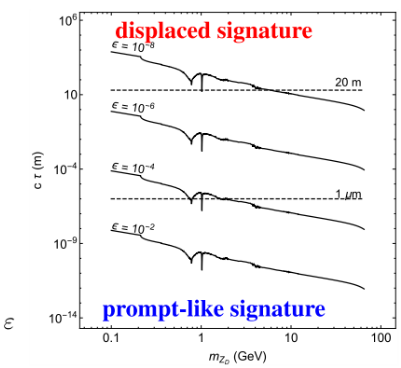


- **TLA**/**data scouting** probes lower mass and similar coupling as traditional searches
- topologies with **ISR** suffer from reduced acceptance:
  - probed couplings/equivalent cross sections are lower

Dark photon framework

Additional broken $U(1)_D$ gauge force in dark (hidden) sector:

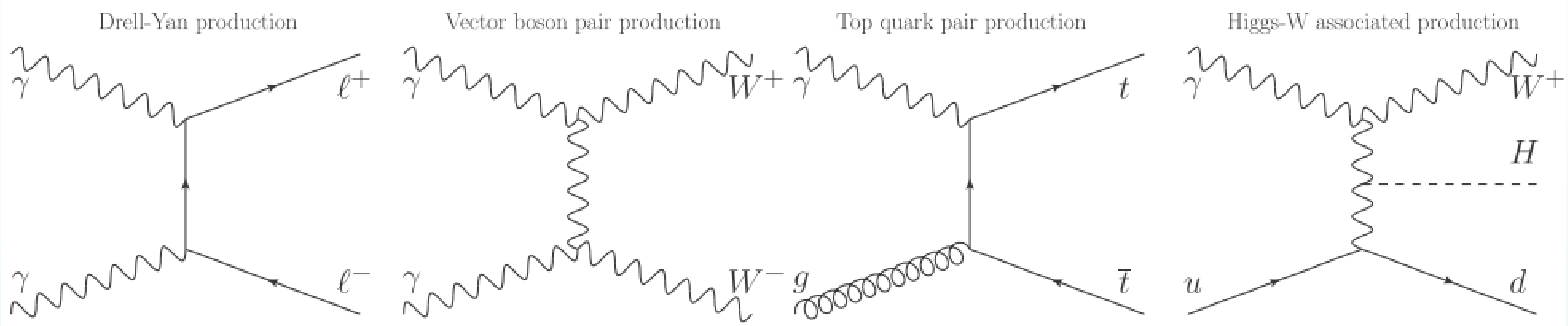
- creates a connection between the SM and possible dark sector
- kinetic mixing term ε induces mixing between dark photon Z_D and the SM photon and Z
- ε impacts Z and SM fermions coupling at $\mathcal{O}(\varepsilon^2)$
- if the dark sector is heavy, dark photons decay to SM particles
- their width and lifetime depend on ε and m_{Z_D}



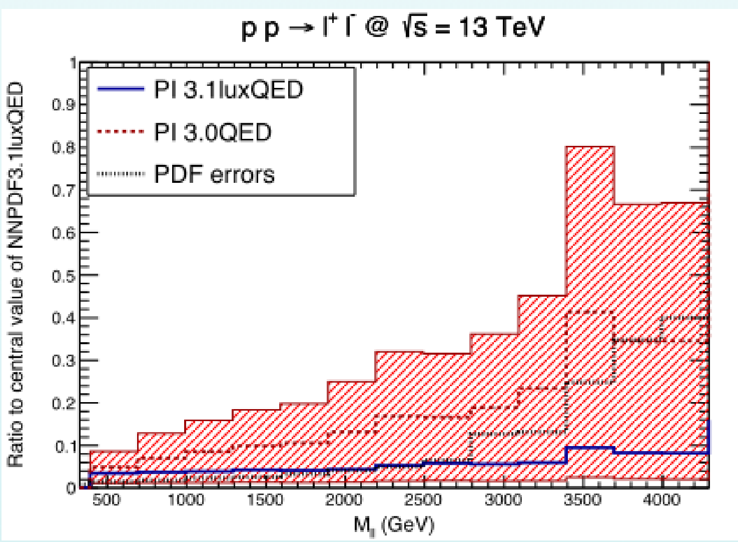
To cover all parameter-space becomes essential to add a new parameter: look for displaced vertices / decay products

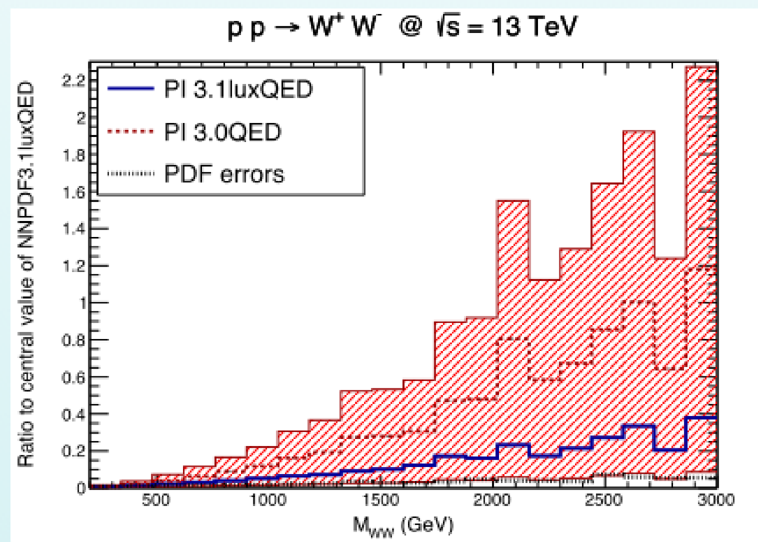
arXiv:1412.0018

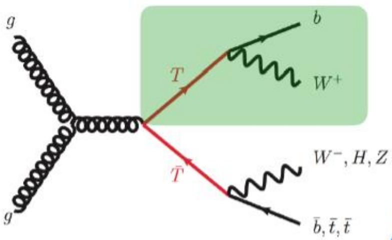
Photon-intiated processes at the LHC

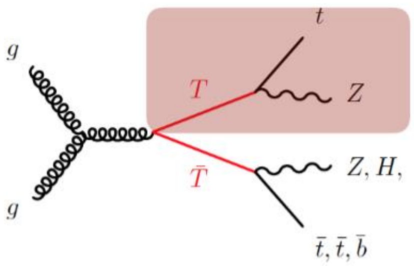


- NNPDF3.1luxQED results are **consistent** with NNPDF3.0QED, with **much reduced uncertainties**
- PI effects can be up to **10% (Drell-Yan) and 30% (WW) at the LHC**, with opposite sign wrt **EW corrections**









Vector Like Quarks

- Masses of VLQ are not generated by a Yukawa coupling, not excluded by existing Higgs measurements
- Apear in Composite Higgs, Little Higgs or extra dimensional models
- The VLQs couple preferentially to 3rd-generation quarks (B, T) have both charged-current and neutral-current decays

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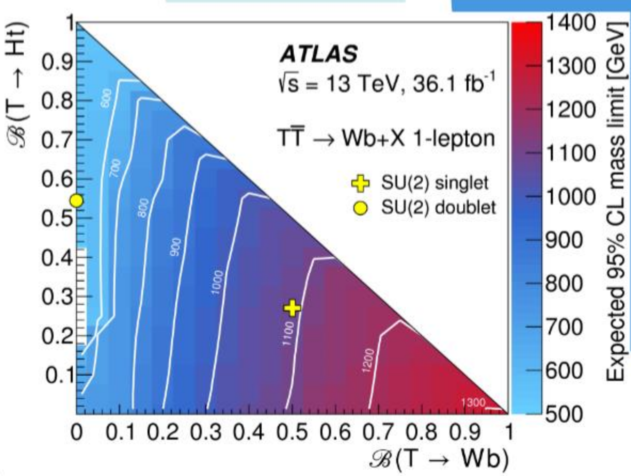

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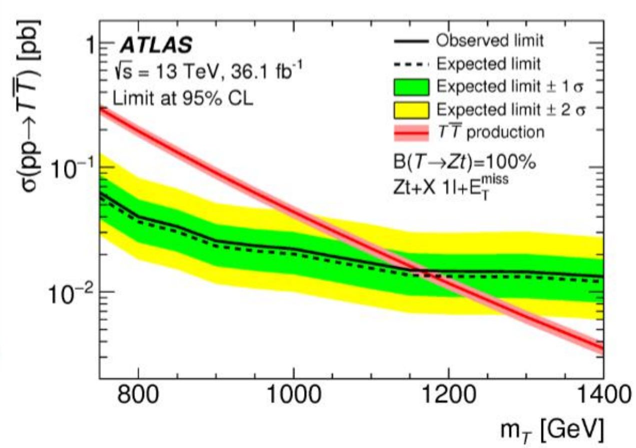
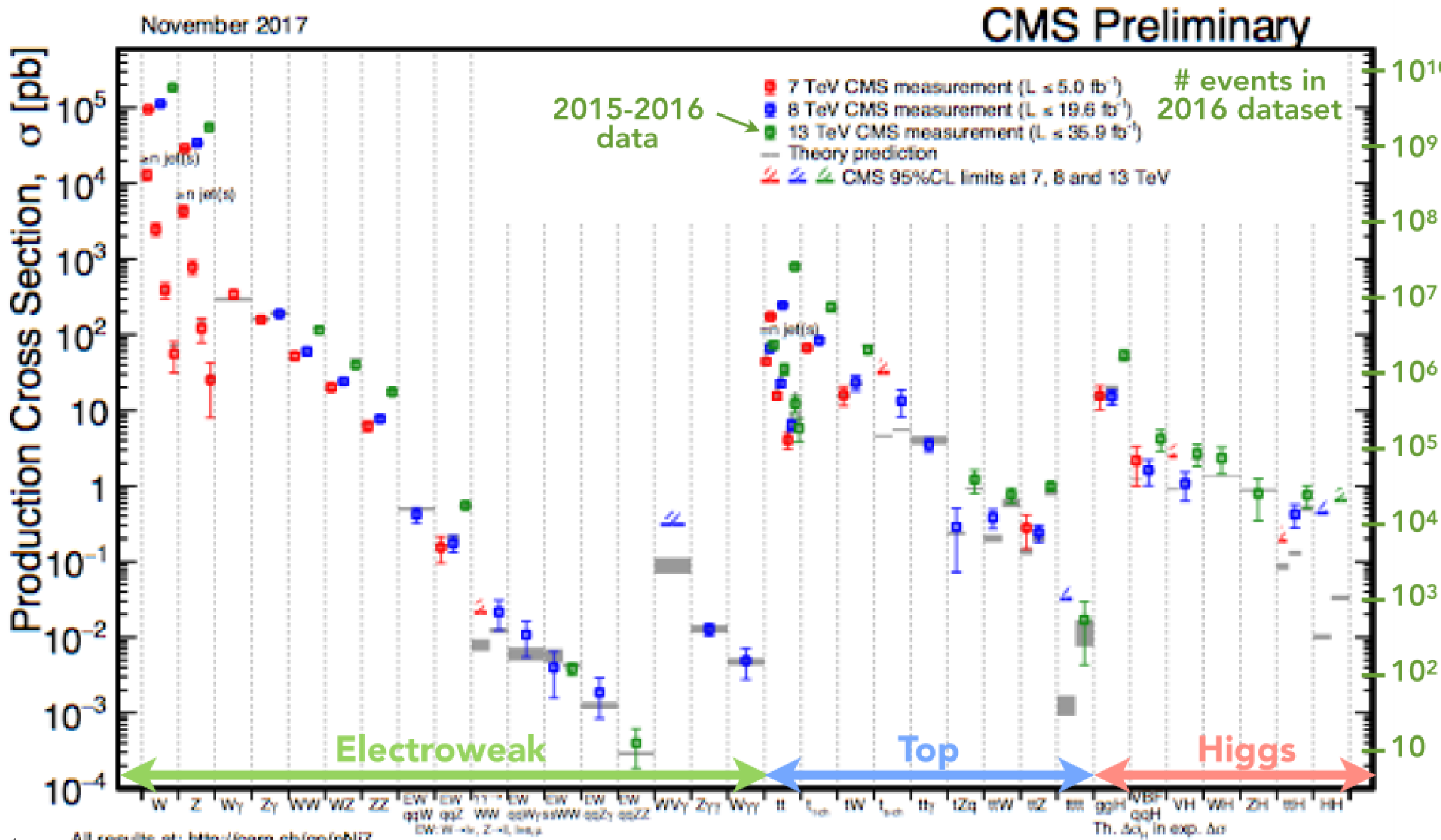


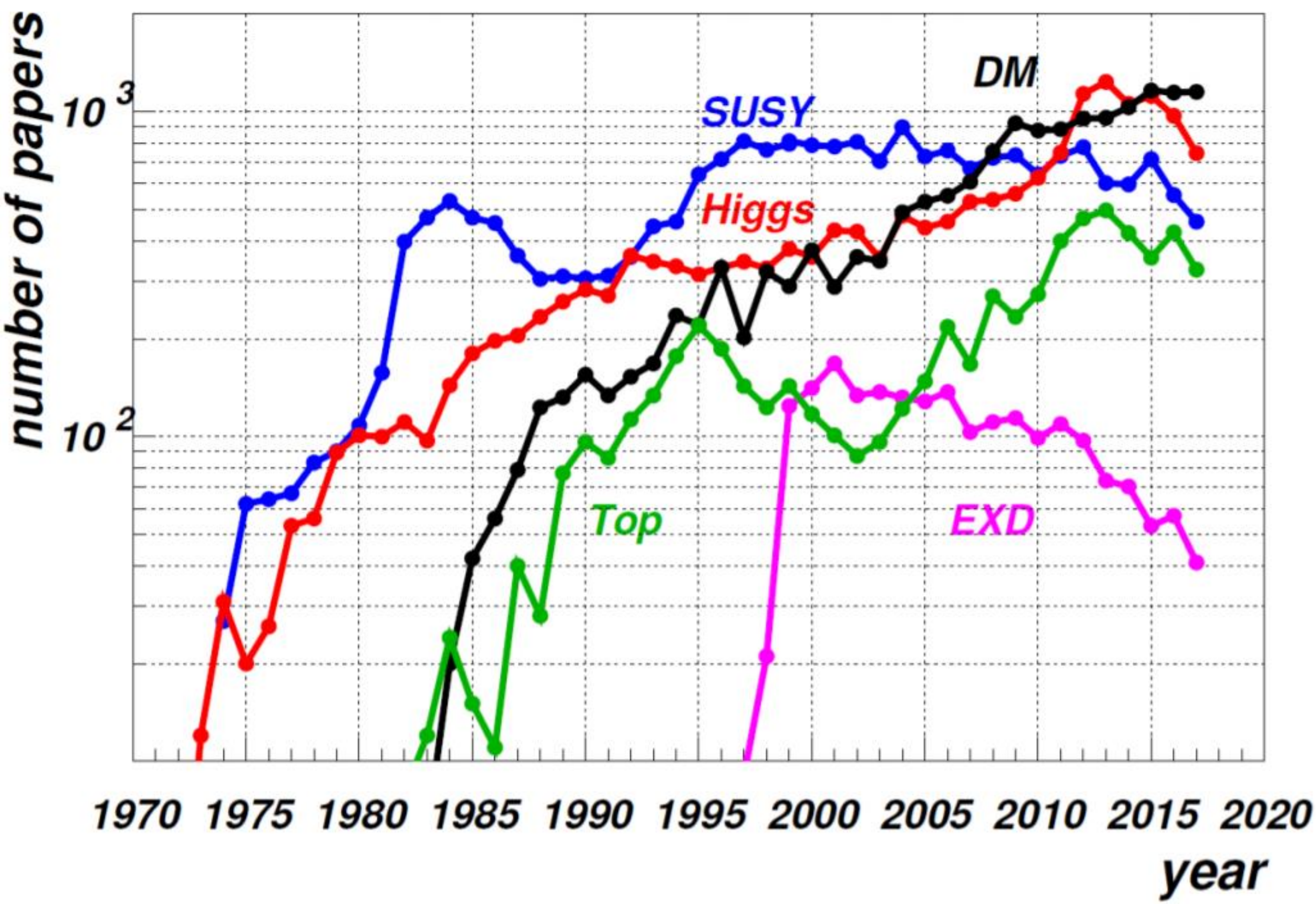
Oliver Stelzer-Chilton, HEP18

Physics highlights

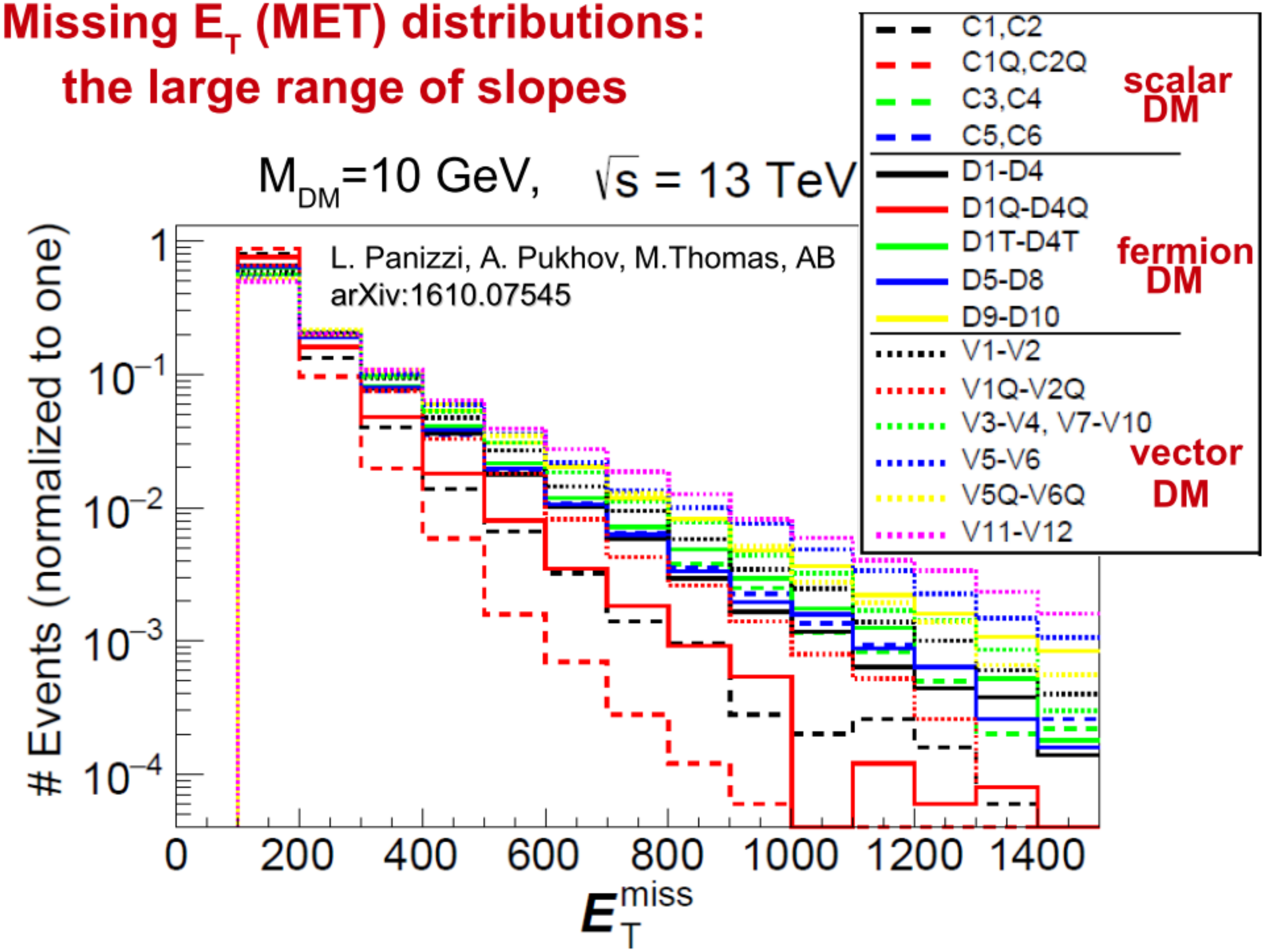


Measurements span **nine** orders of magnitude!

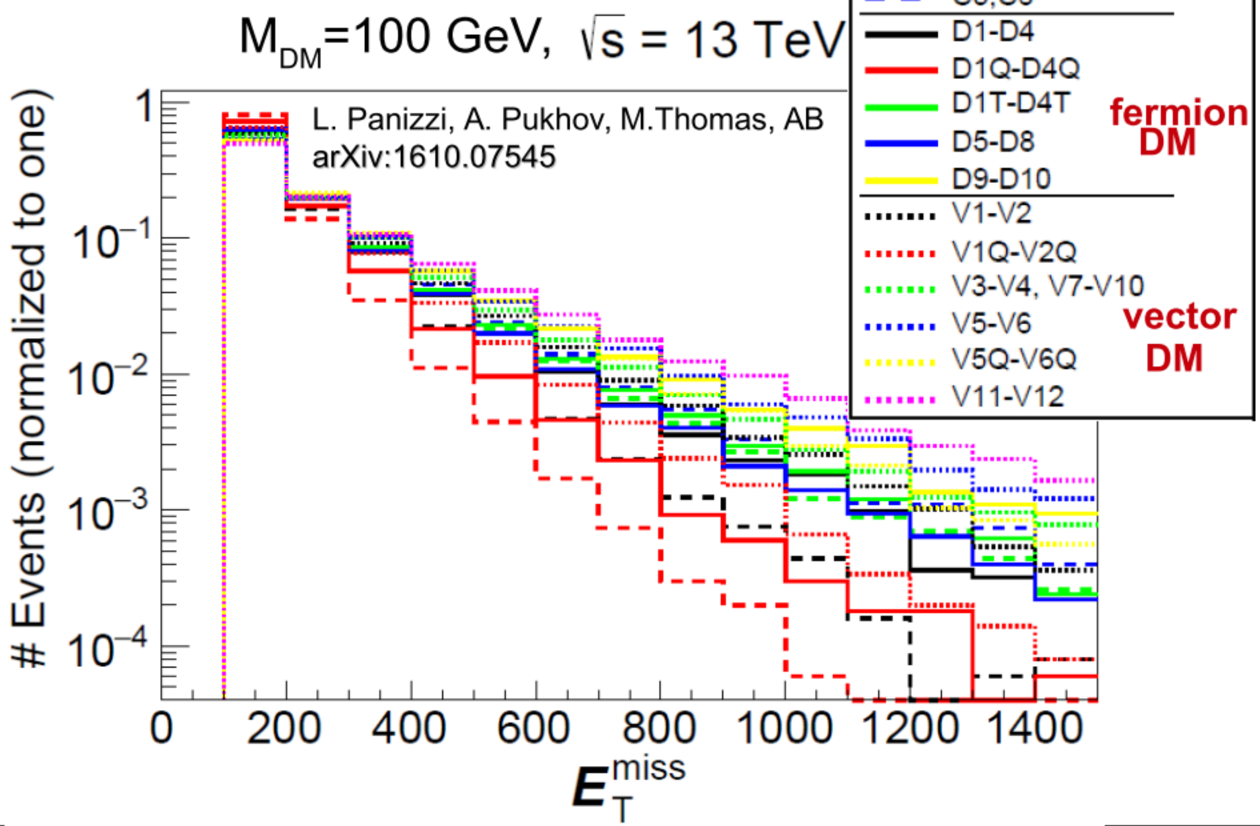
Why we are so keen to study DM?



Missing E_T (MET) distributions: the large range of slopes



M_{DM} dependence is weak for 10-100 GeV range



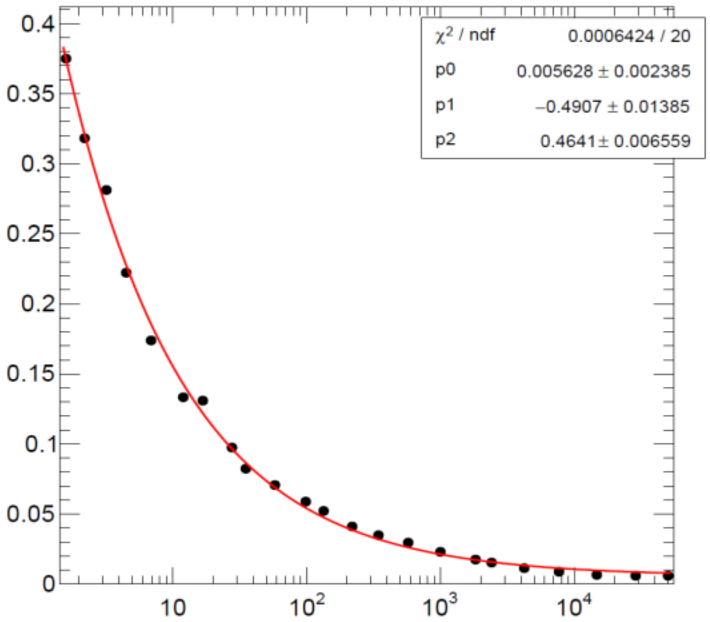
On the BG uncertainty

- **The BG is statistically driven, e.g. pp-> Zj → nnj BG is defined from the pp → Zj → l^+l^-j one**

CMS-PAS-EXO-16-013

E_T^{miss} Range (GeV)	Z($\nu\nu$)+jets	W($\ell\nu$)+jets	Total (Pre-fit)	Total (Post-fit)	Data
200 – 230	14919 ± 221	11976 ± 196	27761 ± 1464	28654 ± 171	28601
230 – 260	7974 ± 116	5776 ± 101	14114 ± 757	14675 ± 97	14756
260 – 290	4467 ± 70	2867 ± 50	7193 ± 351	7666 ± 68	7770
290 – 320	2518 ± 46	1520 ± 34	4083 ± 204	4215 ± 48	4195
320 – 350	1496 ± 35	818 ± 20	2385 ± 118	2407 ± 37	2364
350 – 390	1204 ± 31	555 ± 15	1817 ± 87	1826 ± 32	1875
390 – 430	684 ± 20	275 ± 9	978 ± 45	998 ± 23	1006
430 – 470	382 ± 14	155 ± 6	589 ± 30	574 ± 17	543
470 – 510	248 ± 11	87.3 ± 3.8	337 ± 15	344 ± 12	349
510 – 550	160 ± 8	52.2 ± 2.7	211 ± 9	219 ± 9	216
550 – 590	99.5 ± 6.0	29.2 ± 1.9	134 ± 6	134 ± 7	142
590 – 640	77.3 ± 4.9	18.9 ± 1.4	100 ± 4	98.5 ± 5.8	111
640 – 690	44.8 ± 3.5	11.2 ± 0.9	59.6 ± 2.6	58.0 ± 4.1	61
690 – 740	27.8 ± 2.5	6.1 ± 0.6	36.6 ± 1.5	35.2 ± 2.9	32
740 – 790	21.8 ± 2.3	5.3 ± 0.6	23.8 ± 1.0	27.7 ± 2.7	28
790 – 840	13.5 ± 1.9	2.8 ± 0.4	15.3 ± 0.7	16.8 ± 2.2	14
840 – 900	9.5 ± 1.4	2.0 ± 0.3	12.2 ± 0.6	12.0 ± 1.6	13
900 – 960	5.4 ± 1.0	1.1 ± 0.2	7.6 ± 0.3	6.9 ± 1.2	7
960 – 1020	3.3 ± 0.8	0.77 ± 0.21	5.2 ± 0.3	4.5 ± 1.0	3
1020 – 1160	2.5 ± 0.8	0.52 ± 0.16	3.6 ± 0.2	3.2 ± 0.9	1
1160 – 1250	1.7 ± 0.6	0.3 ± 0.11	2.3 ± 0.1	2.2 ± 0.7	2
> 1250	1.4 ± 0.5	0.19 ± 0.08	1.6 ± 0.1	1.6 ± 0.6	3

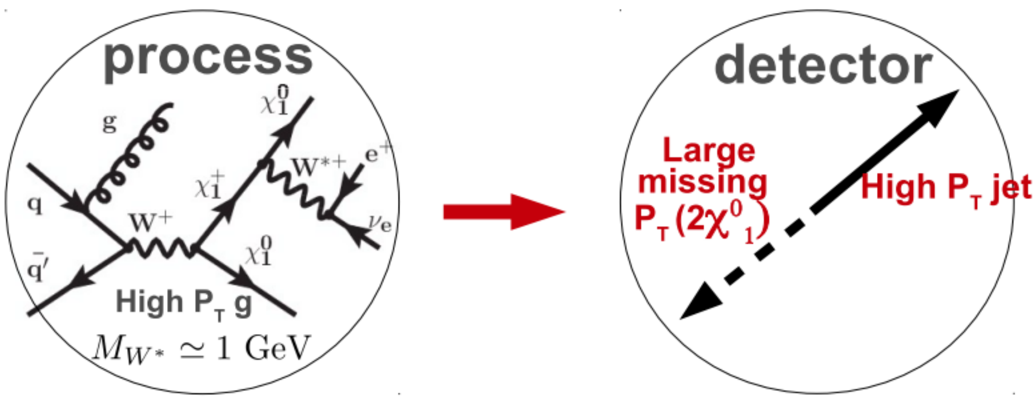
On the BG uncertainty



- The BG is statistically driven, e.g. pp-> Zj → nnj BG is defined from the pp → Zj → l^+l^-j one
- For the high enough statistics the BG error can be as low as 1%, but not much lower than this!
- Once ~ 1% dBG is reached (we assume as a floor), the increase of luminosity does not improve LHC sensitivity: the BG uncertainty linearly grows with luminosity together with signal

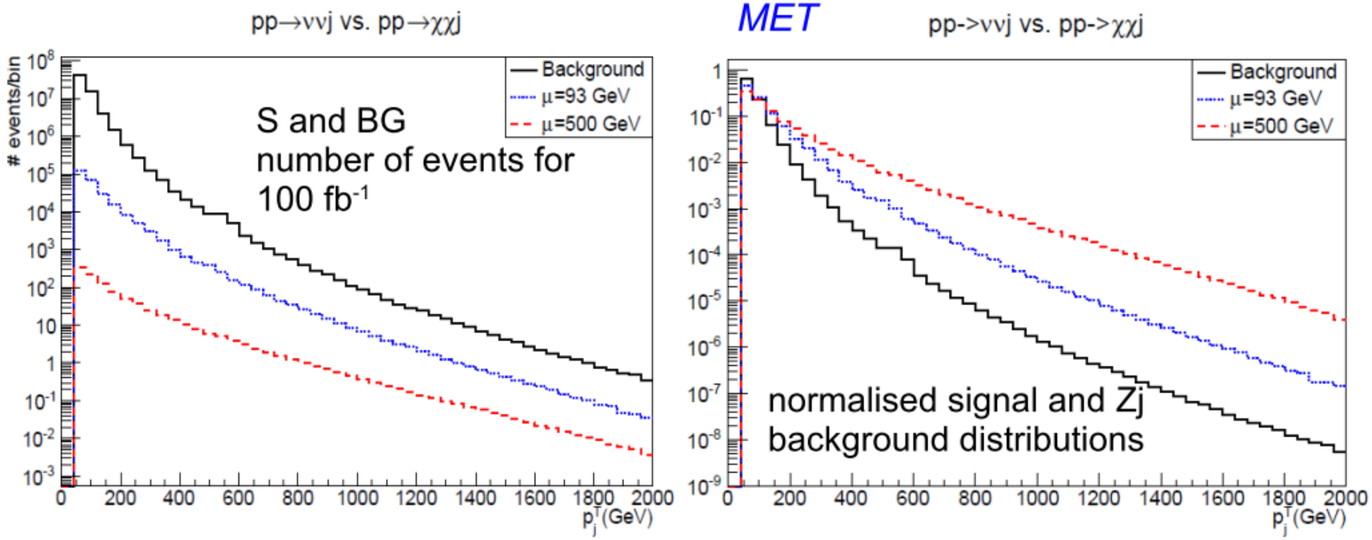
SUSY Compressed Mass Spectrum scenario

- The most challenging case takes place when only $\chi^0_{1,2}$ and $\chi^\pm$ are accessible at the LHC, and the mass gap between them is not enough for any leptonic signature
- The only way to probe CHS is a mono-jet signature
  ["Where the Sidewalk Ends? ..." Alves, Izaguirre,Wacker '11] ,
  which has been used in studies on compressed SUSY spectra, e.g.
  Dreiner,Kramer,Tattersall '12; Han,Kobakhidze,Liu,Saavedra,Wu'13;
  Han,Kribs,Martin,Menon '14



Signal vs Background

- *difference in rates is pessimistic ...*
- *but the difference in shapes is encouraging, especially for large DM mass → biger M(DM,DM) → flatter MET*



Signal and Zj background parton-level p_T^j distributions for the 13 TeV LHC

Remark on EW corrections

For most Higgs physics (e.g. decays, inclusive production) these are under control, known, and small (5% or less, see Spira and Zeppenfeld)

But for more general explorations of EWSB in the high-Q2 regime, they are large, may require NNLO, and the development of dedicated progress

Example: EW corrections to VBS, *Biedermann, Denner, Pellen, arXiv:1611.0295*

$$p_{\mathrm{T,j}} > 30\,\mathrm{GeV}, \quad |y_{\mathrm{j}}| < 4.5, \tag{6}$$
$$p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}, \quad |y_{\ell}| < 2.5. \tag{7}$$

The missing energy is required to fulfill

$$E_{\mathrm{T}}^{\mathrm{miss}} > 40\,\mathrm{GeV}. \tag{8}$$

For the pair of jets, an invariant mass cut and a cut on the difference of the rapidities is applied,

$$M_{\mathrm{jj}} > 500\,\mathrm{GeV}, \quad |\Delta y_{\mathrm{jj}}| > 2.5. \tag{9}$$

Finally, the leptons are required to be isolated,

$$\Delta R_{\ell\ell} > 0.3, \quad \Delta R_{\mathrm{j}\ell} > 0.3, \tag{10}$$

σ^{LO} [fb]	$\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$ [fb]	δ_{EW} [%]
1.5348(2)	1.2895(6)	−16.0

TABLE I: LO and NLO cross section for $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ at 13 TeV at the LHC. The corresponding EW corrections are given in per cent. The digit in parenthesis indicates the integration error.

=> Possible need for resummation. Need to establish reliability of on-shell results w.r.t. full off-shell ones, since the former are more likely to allow for inclusion of NNLO effects

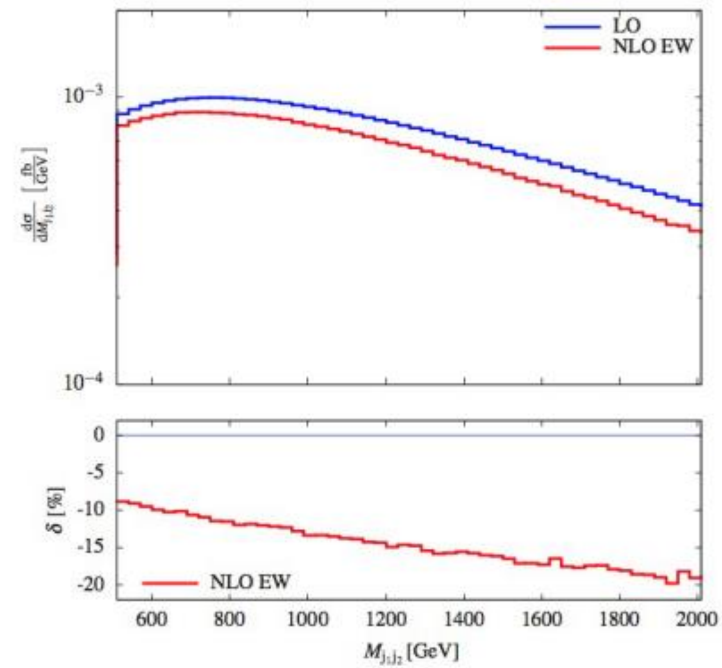
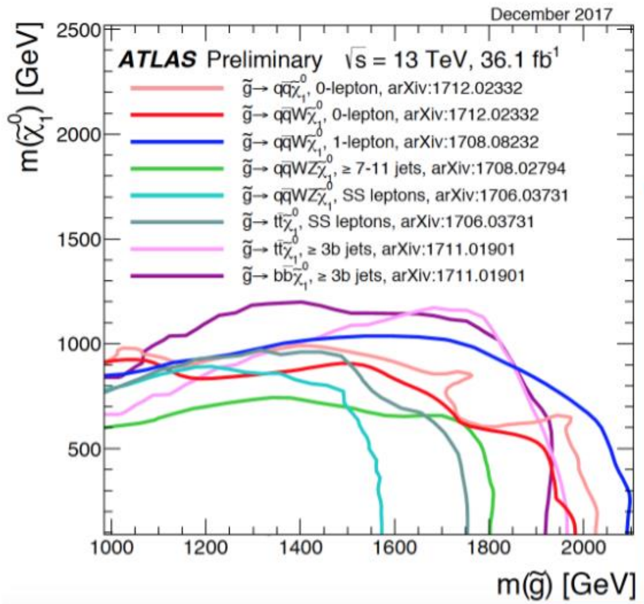
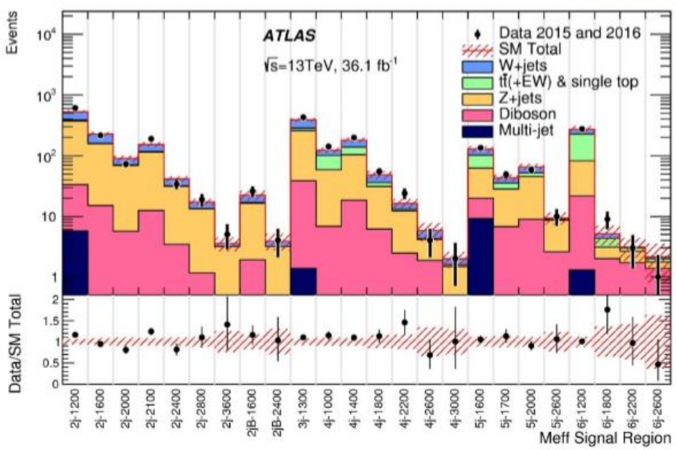


FIG. 1: Dijet invariant-mass distribution in $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ including NLO EW corrections (upper panel) and relative NLO EW corrections (lower panel).

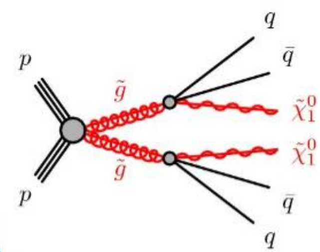
SUSY searches

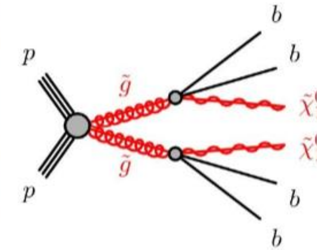


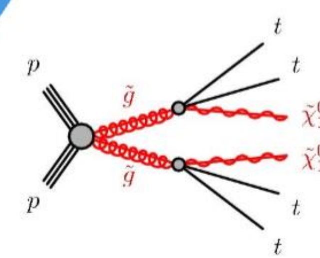


Strong SUSY

- Search for gluinos
- Rich portfolio of analyses with jets, b-jets, leptons and MET in orthogonal signal regions
  - Signal regions with tight cuts
  - Control regions for data-driven background normalization
  - Validation regions
- Effective mass meff = HT + MET as discriminant







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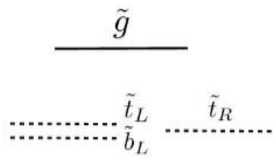
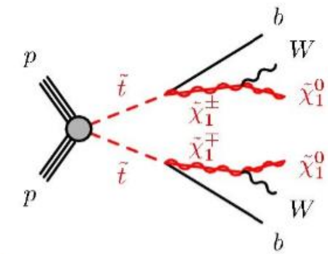
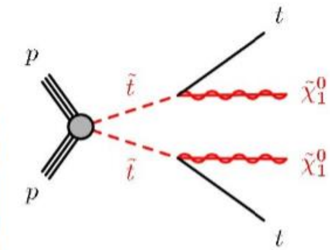


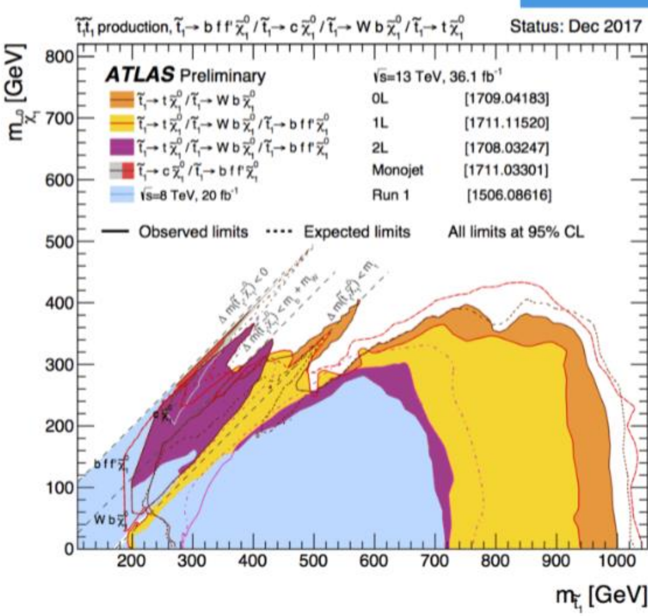
natural SUSY

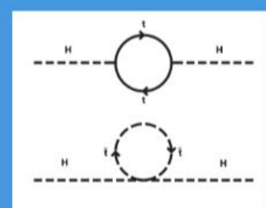
Stop Searches

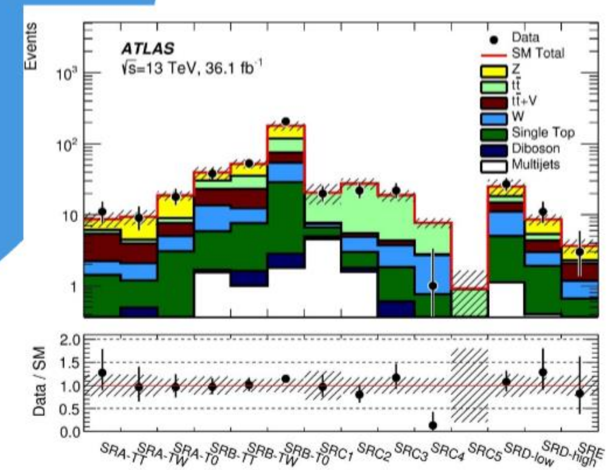
- Stop and sbottoms are expected to be light in natural SUSY
- Main challenge, Z+HF and ttbar backgrounds
- Various searches, including boosted scenarios
  - 0-lepton+b-jets
  - 1-lepton+b jets
  - 2-leptons+b-jets



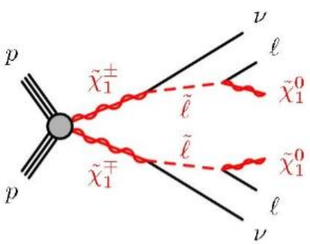


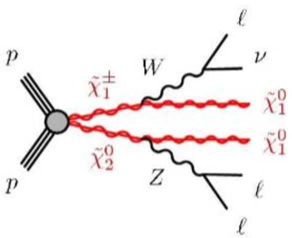






Oliver Stelzer-Chilton, HEP18

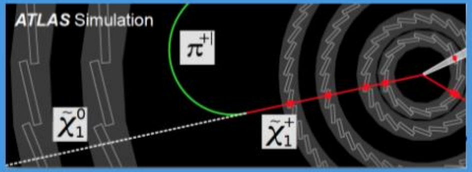


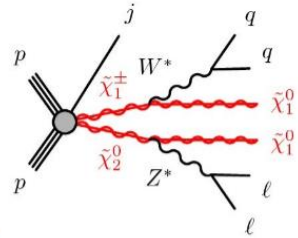


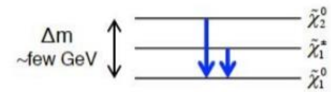
Electroweak SUSY

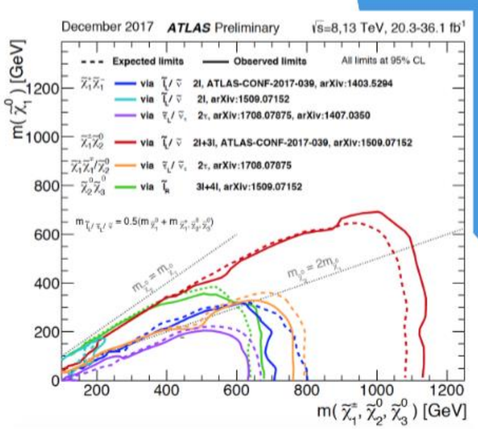
- No sign of strongly produced SUSY motivates search for weakly produced SUSY particles
- Various searches for gauginos, typically
  - 2 or 3 leptons + MET

- Compressed Higgsino spectrum
  - few GeV-level splitting accessible through soft leptons (down to 4 GeV)
  - O(100 MeV) splitting produces longlived charginos: accessible through disappearing tracks

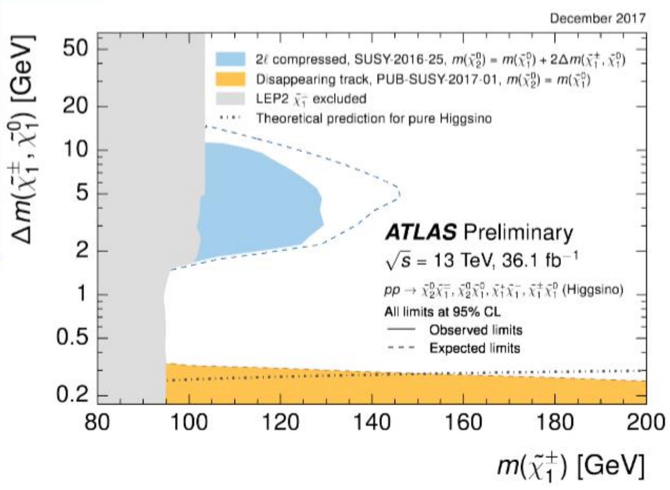








First sensitivity to Higgsino beyond LEP!



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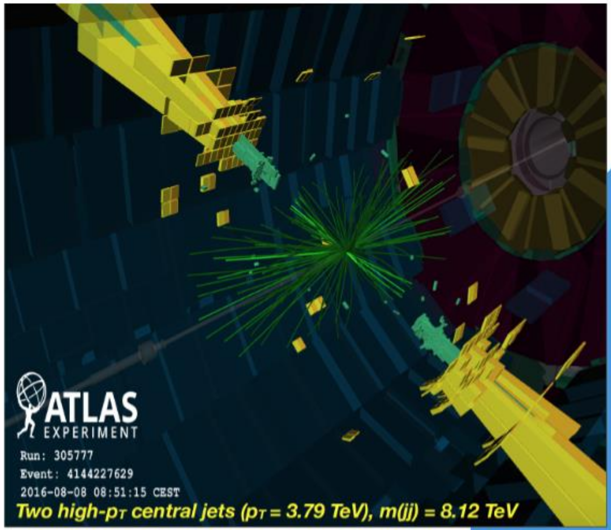
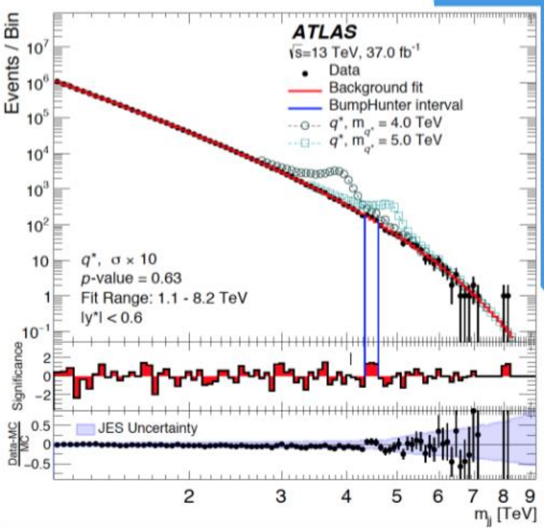
EXOTIC/DM searches

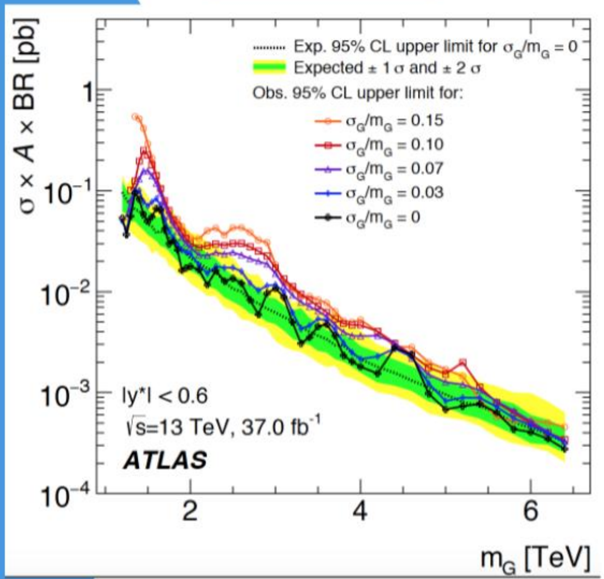
Dijet

arXiv:1703.09127



- Signature: 2 jets with pT > 440 (60) GeV
- Benchmark models: Excited quarks, contact interactions, quantum black holes, W', W* bosons and a range of masses and couplings in a Z' DM mediator model
- Model-independent limit on signals with dijet mass between 1.1 - 6.5 TeV assuming a Gaussian shape
- Trigger level analysis expands sensitivity in low mass region





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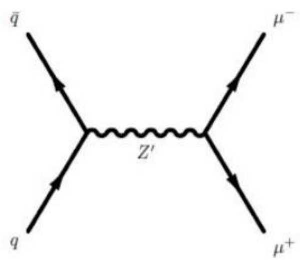
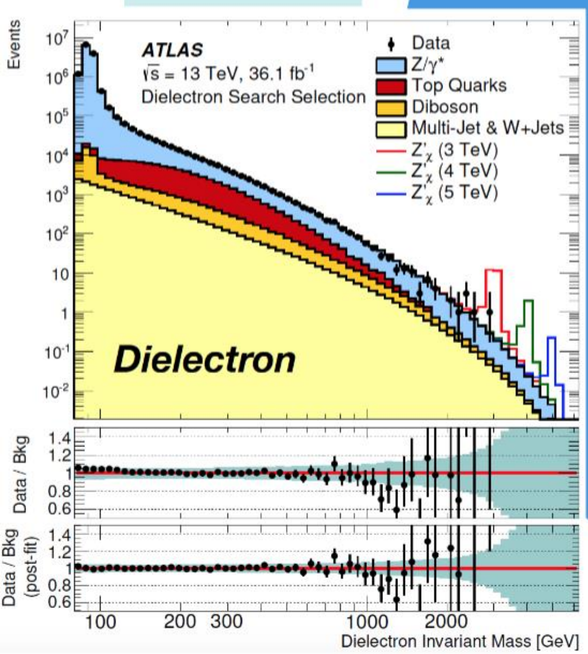
Dilepton



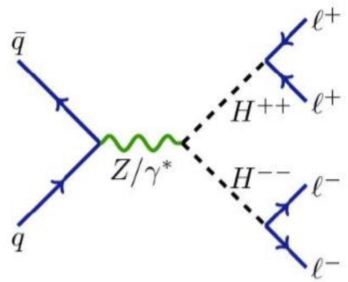
arXiv:1707.02424



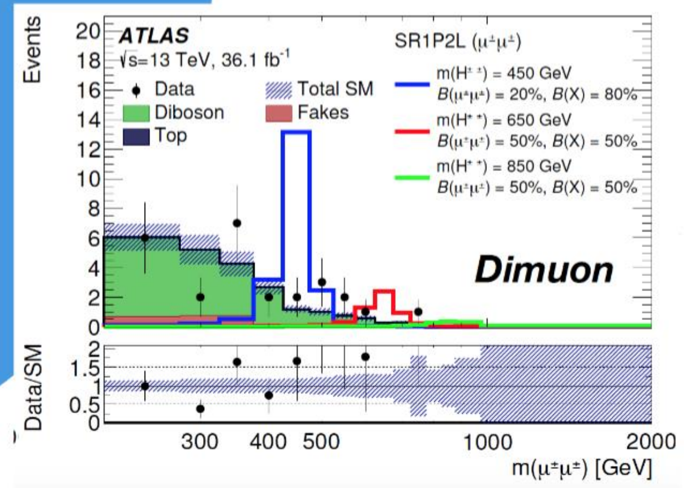
- A pair of electron or muon
- Fully reconstructed, high signal efficiency

- Opposite sign
  - New narrow resonance
  - Well-understood backgrounds
  - SSM Z' M>4.5 TeV

- Same sign
  - Doubly charged Higgs
  - Low irreducible background, care has to be taken for fake backgrounds
  - H+-/+- > 770 - 870 GeV



arXiv:1710.09748



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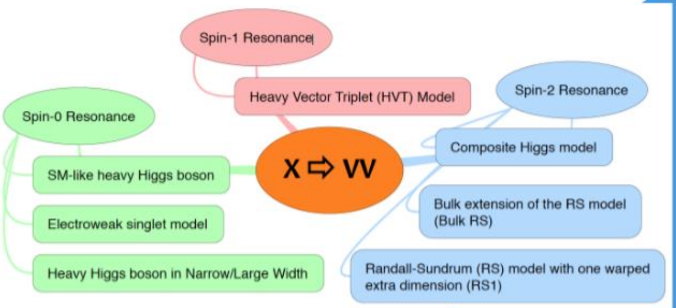
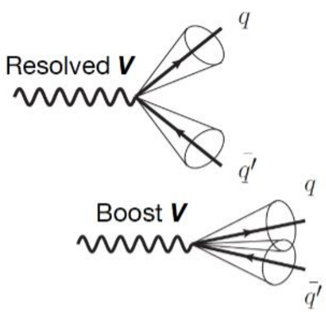
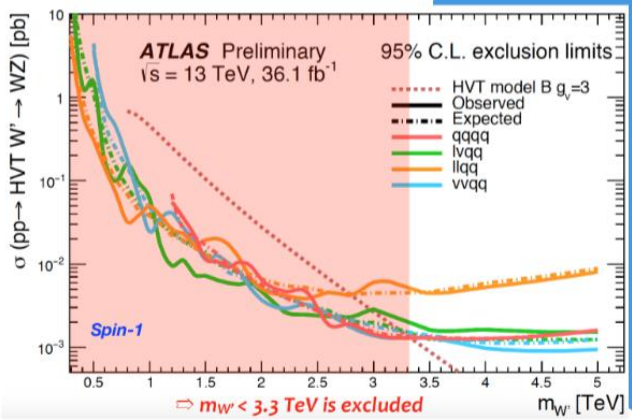
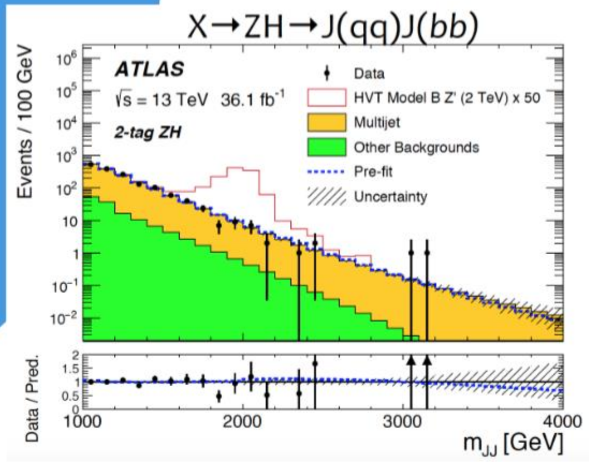
Diboson





- Many models predict the existence of new heavy resonances decaying into diboson
- Various combinations of jets, leptons and MET in the final state
- Tagging hadronic decay of W/Z/H using boosted topologies
- Interpretations in spin 0/1/2 cases





arXiv:1707.06958, 1710.07235, 1708.04445, 1708.09638, 1712.06518

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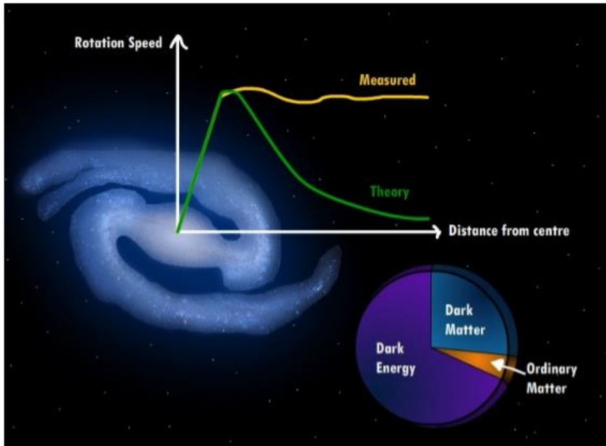
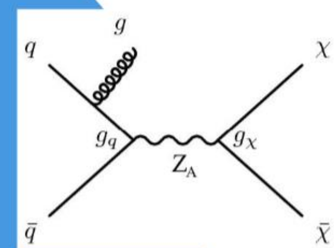
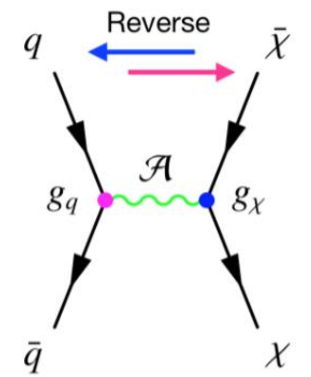


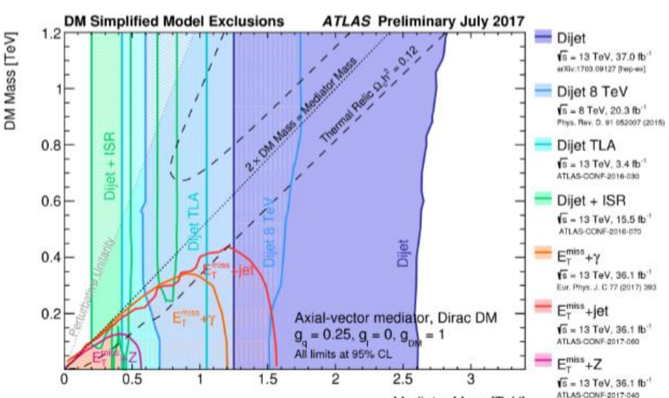
Dark Matter

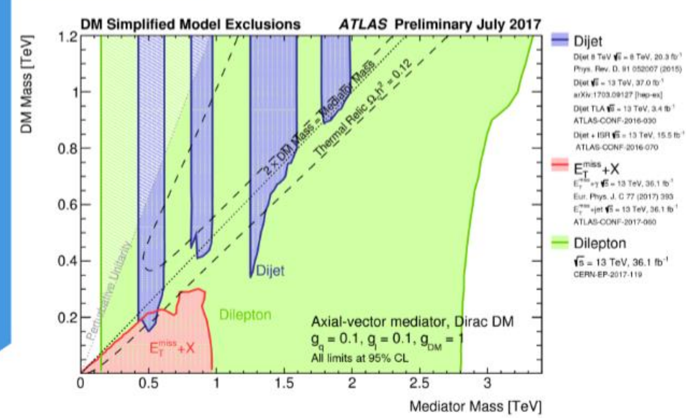
- Generic dark matter models tested with searches for mono-jet/photon/W,Z/ Higgs + MET, with recoil against invisible dark matter particles
- Complementary to direct searches
- Rich phenomenology depends on mass of DM, mass of heavy mediator and value and type of couplings

- Recast the limits from interpretations of dijet and dilepton resonance searches









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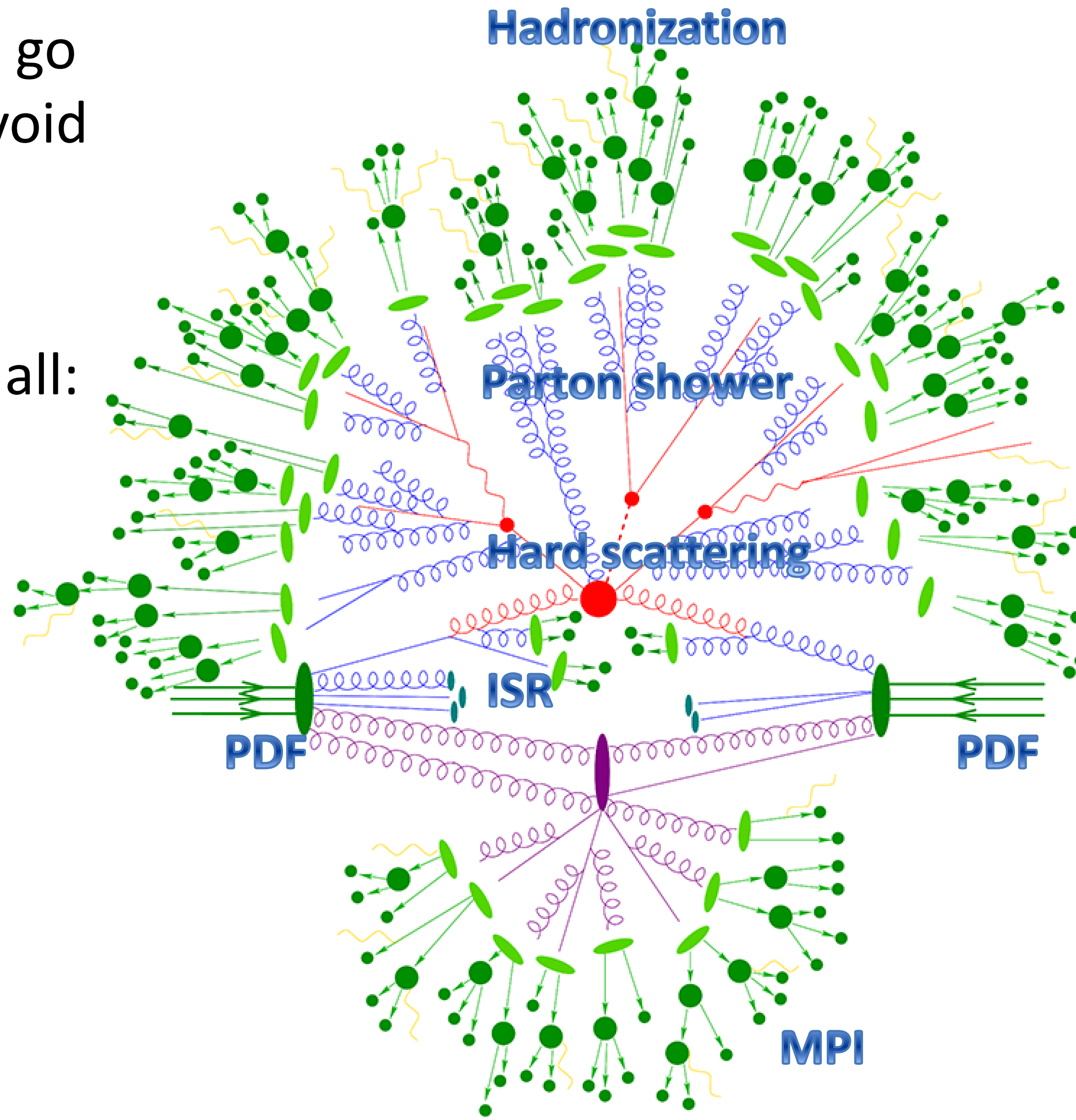
Even more complicated than that

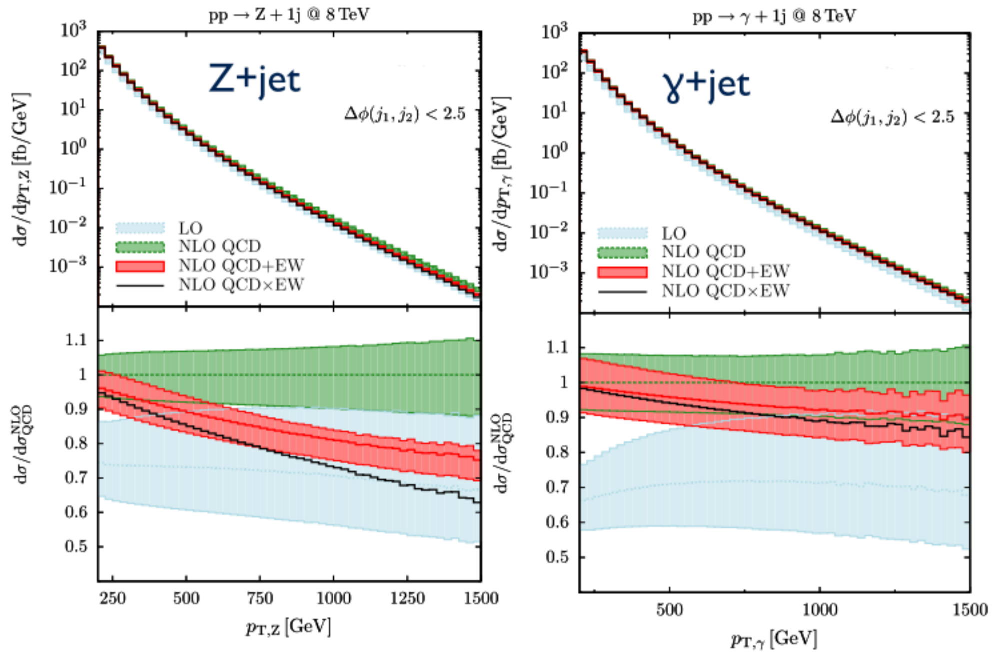
- If you want (or need…) to go for precision, you can't avoid the nitty gritty details…

- You have to pursue them all:
  - **PDF**
  - **Hard scattering**
    - **Fixed order**
    - **Matched**
    - **ISR**
  - **Parton shower**
  - **Hadronization**
  - **Underlying Event**
  - **Multi-parton interaction**



https://theory.slac.stanford.edu/our-research/simulations

Prelude: Z+jet vs. γ + 1 jet



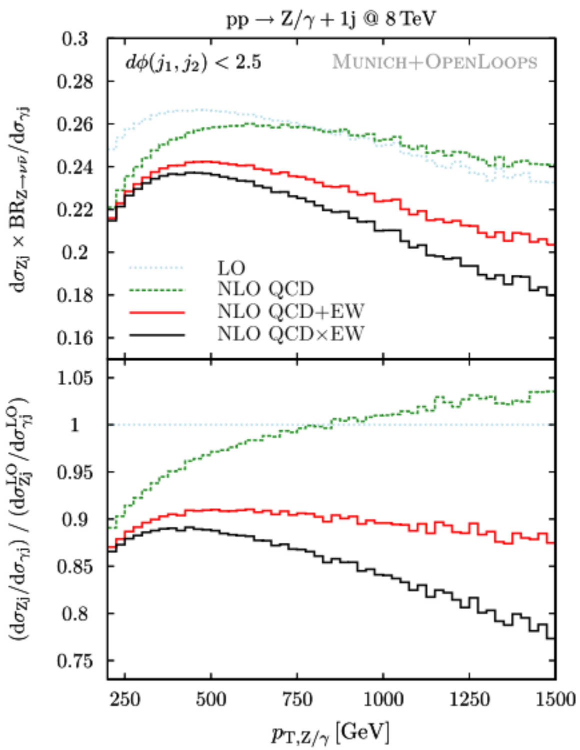
QCD corrections

- mostly moderate and stable QCD corrections
- (almost) **identical QCD corrections in the tail**, sizeable differences for small pT

EW corrections

- **correction in pT(Z) > correction in pT(γ)**
- **-20/-8%** for Z/γ at 1 TeV
- EW corrections > QCD uncertainties for $p_{T,Z}$ > 350 GeV

Prelude: Z/γ pT-ratio



Overall

- mild dependence on the boson pT

QCD corrections

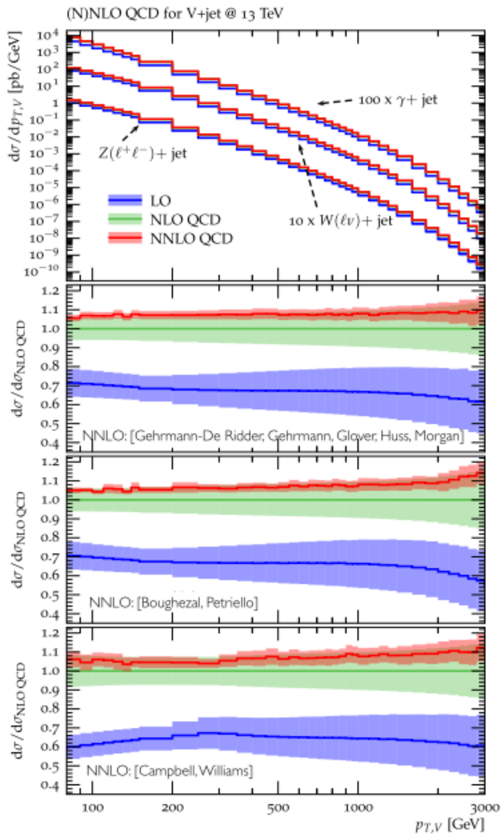
- 10-15% below 250 GeV
- ≲ 5% above 350 GeV

EW corrections

- sizeable difference in EW corrections results in 10-15% corrections at several hundred GeV
- ~5% difference between NLO QCD+EW and NLO QCDxEW

Pure QCD uncertainties

Z
W
γ



$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{QCD}} = \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{NLO\,QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{NNLO\,QCD}}$$

$$\boxed{\mu_0 = \frac{1}{2}\left(\sqrt{p^2_{\mathrm{T},\ell^+\ell^-} + m^2_{\ell^+\ell^-}} + \sum_{i\in\{q,g,\gamma\}} |p_{\mathrm{T},i}|\right)}$$

this is a ‘good’ scale for V+jets

- at large pTV: HT’/2 ≈ pTV
- modest higher-order corrections
- sufficient convergence

scale uncertainties due to 7-pt variations:

O(20%) uncertainties at LO
O(10%) uncertainties at NLO
O(5%) uncertainties at NNLO

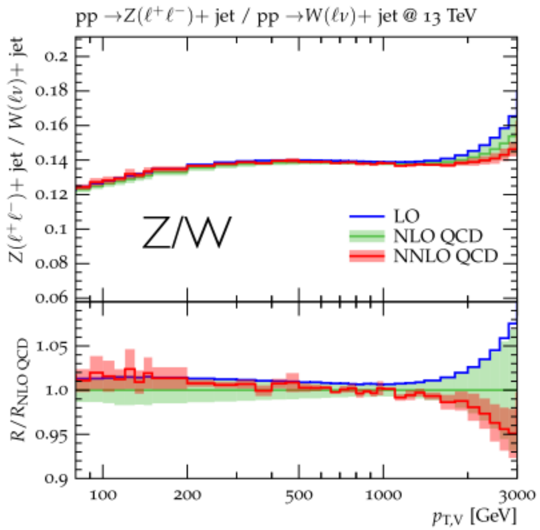
with minor shape variations

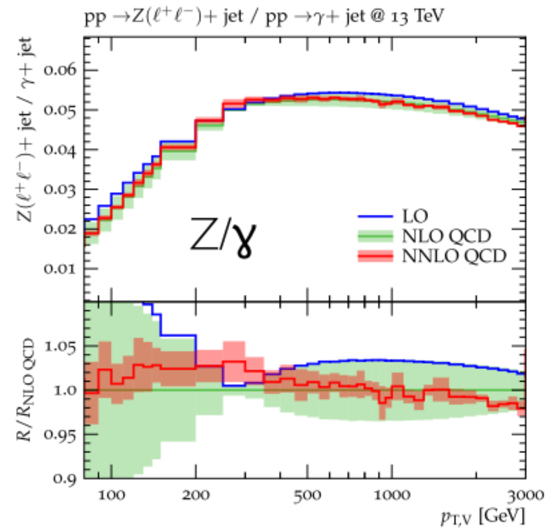
How to correlate these uncertainties across processes?

QCD uncertainties: ratios

How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated:
  NLO QCD uncertainties cancel at the <~ 1 % level
- introduce **process correlation uncertainty** based on K-factor difference: $\delta K_{\mathrm{(N)NLO}} = K^{V}_{\mathrm{(N)NLO}} - K^{Z}_{\mathrm{(N)NLO}}$
  → effectively degrades precision of last calculated order





Uncertainty estimates at NNLO QCD

check against NNLO QCD!

δ < 2 %   δ < 3-4 %

Uncertainties and estimates

(N)NLO QCD + (n)NLO EW

how to correlate scale uncertainties in ratios?

how to estimate uncertainties due to missing higher-order EW?

how to combine higher-order QCD and EW correction?
what is the related uncertainty?

Indirect Higgs probes of new physics at large statistics

M. Mangano HC16

- Higher statistics shifts the balance between systematic and statistical uncertainties. It can be exploited to define different signal regions, with better S/B, better systematics, pushing the potential for better measurements beyond the "systematics wall" of low-stat measurements.

- We often talk about "**precise**" Higgs measurements. What we actually aim at, is "**sensitive**" tests of the Higgs properties, where *sensitive* refers to the ability to reveal BSM behaviours.

- *Sensitivity* may not require extreme precision

  - Going after "sensitivity", rather than *just* precision, opens itself new opportunities …

The progress in exptl analyses and sensitivities has been matched by the results of immense efforts in the modeling of TH production and decay properties

M. Mangano HC16

… as documented in HXSWG reports I-IV , arXiv:1101.0593, 1201.3084, 1307.1347, 1610.07922

Plenary reviews of SM predictions:
SM precision predictions for Higgs partial widths: Spira
Higgs production through gluon fusion: Gehrmann
Higgs production through Weak Boson Fusion: Zeppenfeld
SM tth production, signal & backgrounds: Reina
Off-shell and boosted Higgs production: Caola
Monte Carlo simulation & uncertainties: Schönherr

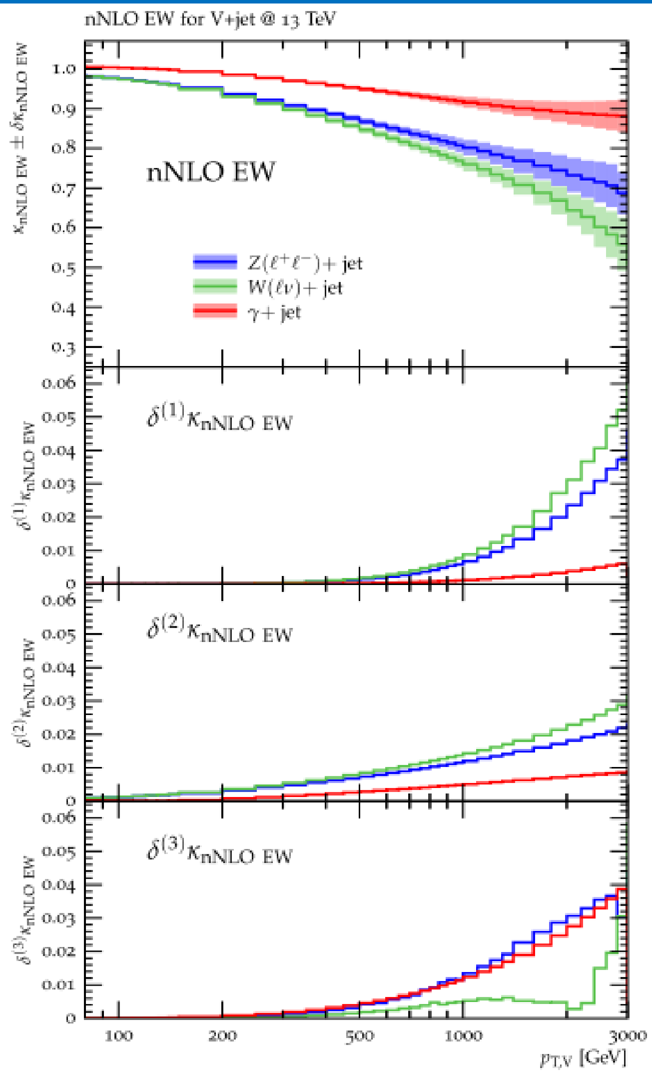
Parallel session contributions on SM predictions:
Parton distributions for high precision measurements at the LHC: Kassabov Zaharieva
Precision Higgs physics at N3LO, Dulat
Differential distributions for Higgs signals at 13 TeV: Specchia
Towards differential Higgs production at N3LO: Mistlberger
Higgs Boson Pair Production at NLO in QCD with Full Top-Quark Mass Dependence: Jones

N3LO is (almost) the new NNLO, but NNLO+PS is not yet the new NLO+PS

Message:

- *by and large,* today's studies of Higgs production and properties are not limited by TH systematics *(see one of the possible exceptions next …)*
- there is no reason to doubt that future TH progress will match the reduction of statistical and exptl syst's, all the way through to the HL-LHC phase … *of course it will cost sweat and blood, but a **bright, motivated, committed and rewarded** community of **young** theorists is in continuous growth*
- a strong program of dedicated measurements, necessary for the validation and tuning of calculations and tools must remain integral part of the exptl priorities

EW uncertainties



nNLO EW corrections at 1 TeV

- -10% for γ+jets
- -20% for Z+jet
- -25% for W+jet

$$\mathrm{d}\sigma_{\mathrm{EW}} = \left[1 + \frac{\alpha}{\pi}\left(\delta^{(1)}_{\mathrm{hard}} + \delta^{(1)}_{\mathrm{Sud}}\right) + \left(\frac{\alpha}{\pi}\right)^2\left(\delta^{(2)}_{\mathrm{Sud}} + \delta^{(1)}_{\mathrm{Sud}}\delta^{(1)}_{\mathrm{hard}} + \delta^{(1)}_{\mathrm{hard}}\delta^{(1)}_{\mathrm{hard}} + \delta^{(2)}_{\mathrm{hard}}\right) + \left(\frac{\alpha}{\pi}\right)^3\left(\delta^{(3)}_{\mathrm{Sud}} \ldots\right)\right]$$

- 'higher-order Sudakov logs'

$$\delta^{(1)}\kappa^{(V)}_{\mathrm{EW}}(x) \quad = \quad \frac{2}{3}\kappa^{(V)}_{\mathrm{NLO\ EW}}(x)\,\kappa^{(V)}_{\mathrm{NNLO\ Sud}}(x)$$

(correlated)

Additional uncorrelated uncertainties:

- 'hard non-log NNLO EW effects I'

$$\delta^{(2)}\kappa^{(V)}_{\mathrm{EW}}(x) = 0.05\,\kappa^{(V)}_{\mathrm{NLO\ EW}}(x)$$

(uncorrelated)

$$\Leftrightarrow \quad \delta^{(2)}_{\mathrm{hard}} \leq \frac{0.05\pi}{\alpha}\delta^{(1)}_{\mathrm{hard}} \simeq 20\,\delta^{(1)}_{\mathrm{hard}}$$

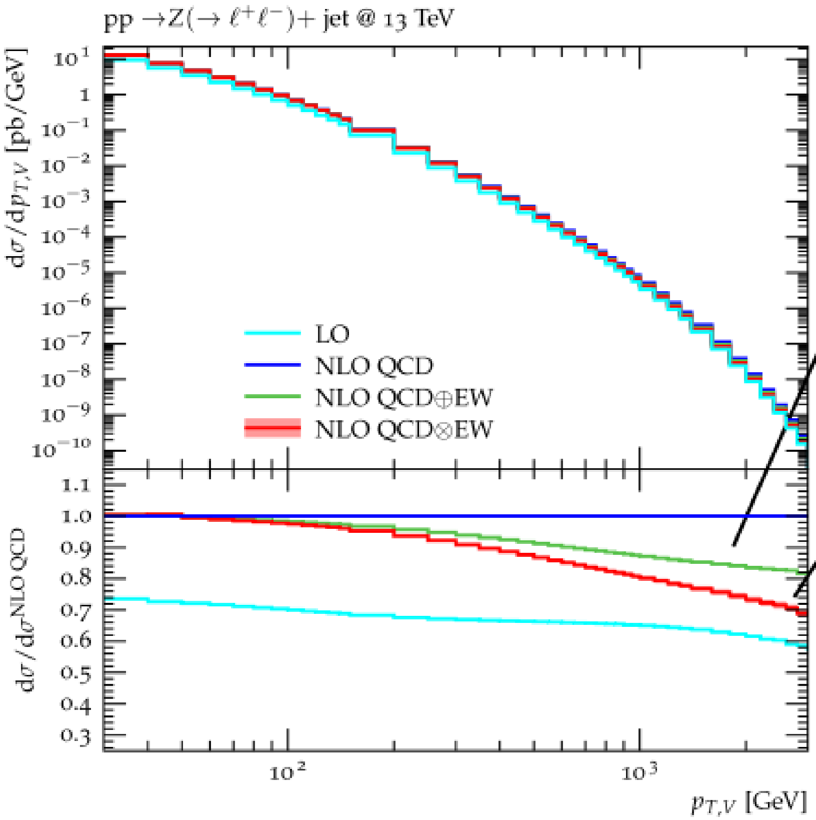
- 'hard non-log NNLO EW effects II'

$$\delta^{(3)}\kappa^{(V)}_{\mathrm{EW}}(x) \quad = \quad \kappa^{(V)}_{\mathrm{NNLO\ Sud}}(x) - \frac{1}{2}\left[\kappa^{(V)}_{\mathrm{NLO\ EW}}(x)\right]^2$$

(uncorrelated)

estimate of typical size of $\left[\delta^{(1)}_{\mathrm{hard}}\right]^2$ or $\delta^{(1)}_{\mathrm{hard}} \times \delta^{(1)}_{\mathrm{Sud}}$.

Mixed QCD-EWK uncertainties



Given QCD and EW corrections are sizeable, also mixed QCD-EW uncertainties of relative $\mathcal{O}(\alpha\alpha_s)$ have to be considered.

Additive combination

$$\sigma^{\mathrm{NLO}}_{\mathrm{QCD+EW}} = \sigma^{\mathrm{LO}} + \delta\sigma^{\mathrm{NLO}}_{\mathrm{QCD}} + \delta\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$$

Multiplicative combination

$$\sigma^{\mathrm{NLO}}_{\mathrm{QCD\times EW}} = \sigma^{\mathrm{NLO}}_{\mathrm{QCD}} \left(1 + \frac{\delta\sigma^{\mathrm{NLO}}_{\mathrm{EW}}}{\sigma^{\mathrm{LO}}}\right)$$

(try to capture some $\mathcal{O}(\alpha\alpha_s)$ contributions, e.g. EW Sudakov logs × soft QCD)

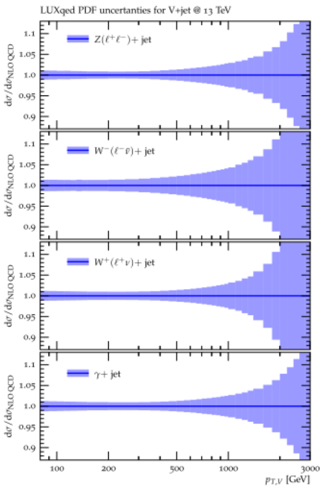
Difference between these two approaches indicates size of missing mixed EW-QCD corrections.

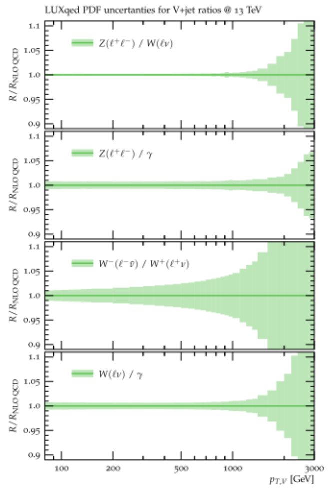
$$K_{\mathrm{QCD\otimes EW}} - K_{\mathrm{QCD\oplus EW}} \sim 10\% \quad \text{at 1 TeV}$$

Too conservative!?

For dominant Sudakov EW logarithms factorization should be exact!

PDF uncertainties (LUXqed=PDF4LHC)

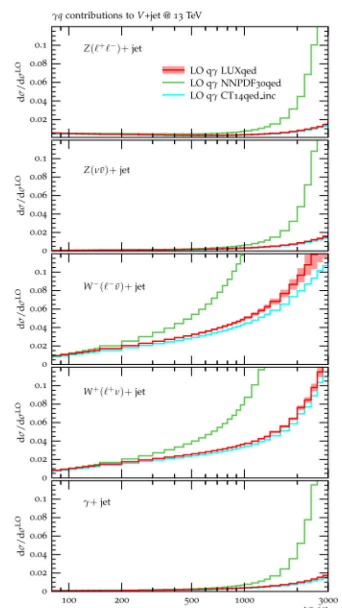




- δ_{PDF} < 2 % for pT,V < 800 GeV
- δ_{PDF} < 5 % for pT,V < 1500 GeV

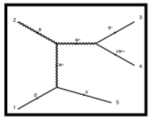
- Z/W: δ_{PDF} < 0.5%(2%) for pT,V < 800 GeV(1.5 TeV)
- Z/γ & W/γ: δ_{PDF} < 2% for pT,V < 1.3 TeV
- W-/W+: δ_{PDF} > 5% for pT,V < 1 TeV
(due to large uncertainties on u/d ratio at large Bjorken-x)

Photon-induced production



- suppressed by relative factor α/α_S
- irrelevant for Z+jet (and γ+jet)
- in W+jet O(5%) contribution with LUXqed, consistent with CT14qed

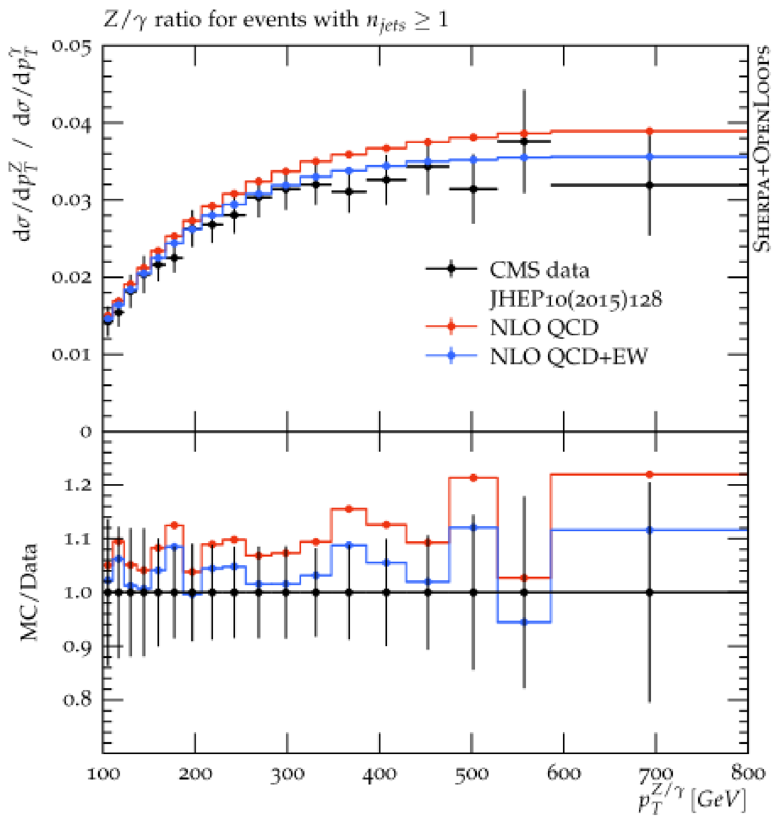
(due to t-channel enhancement)



- ~1% uncertainties in photon PDFs due to LUXqed

Prelude

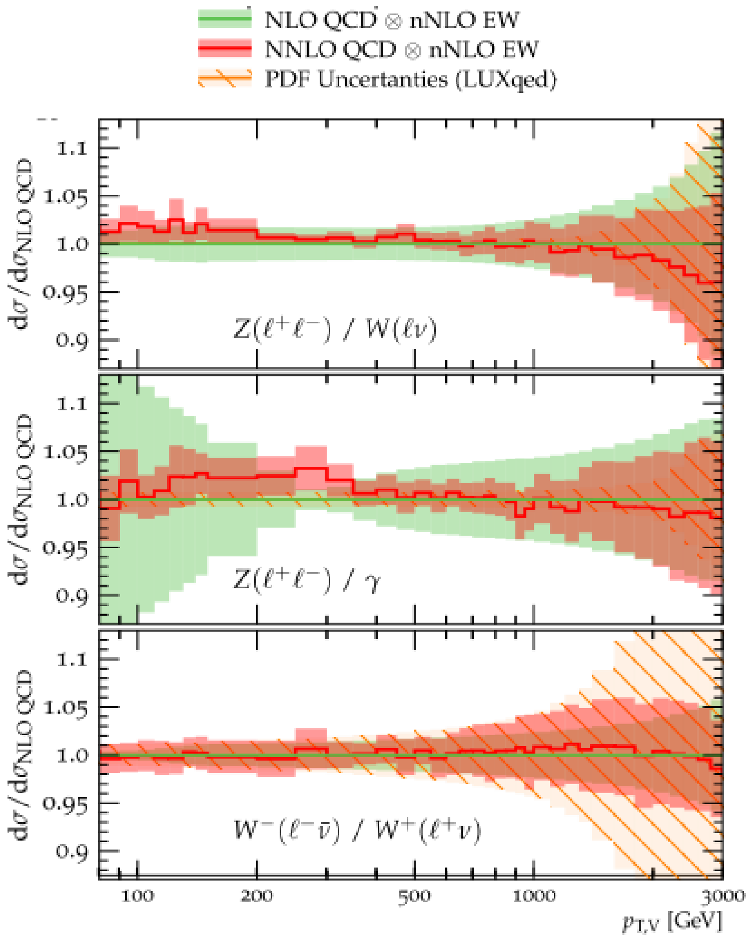
Prelude: compare against Z/γ-data [JHEP10(2015)128]

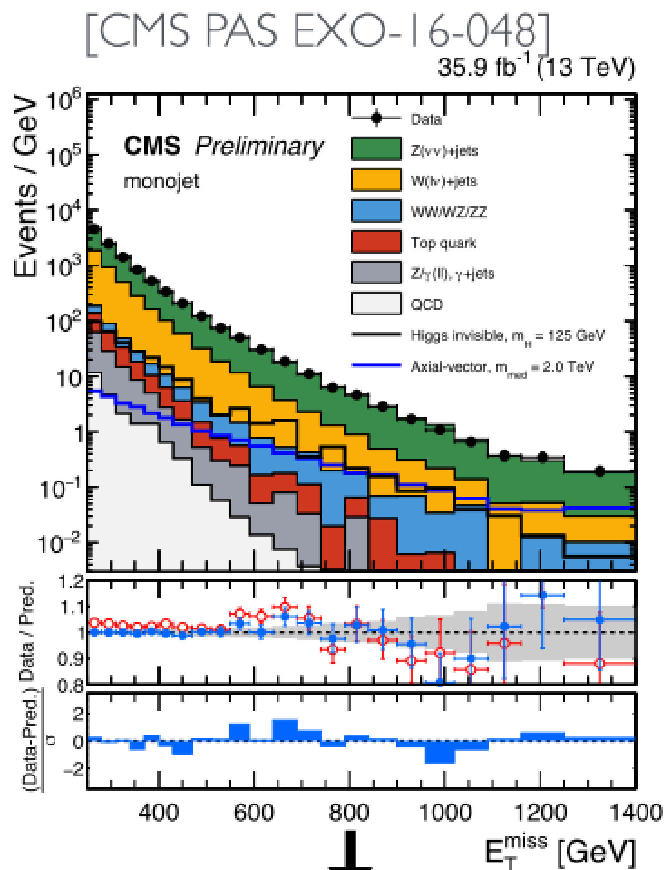


*[Ciulli, Kallweit, JML, Pozzorini, Schönherr for **LesHouches'15**]*

- remarkable agreement with data at @ NLO QCD+EW!

Combined uncertainties on V+jets ratios

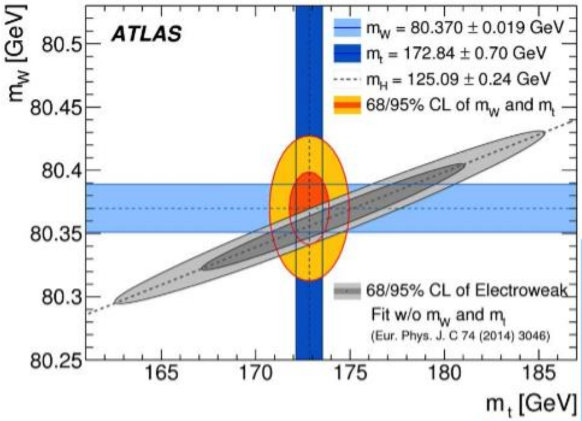




- $\delta_{Z/W}$ =1-3% for pT < 1 TeV
- $\delta_{Z/\gamma}$ = 3-5% for pT < 1 TeV
- $\delta_{W/W}$ < 3% for pT < 2 TeV

Unprecedented limits on monojet DM production!

Thanks W mass!

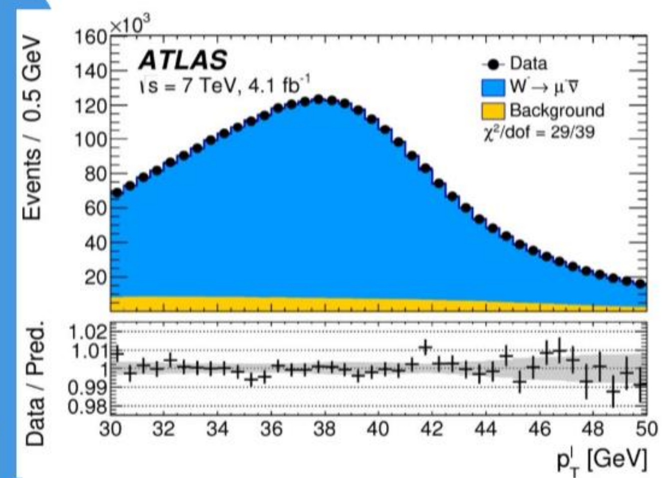


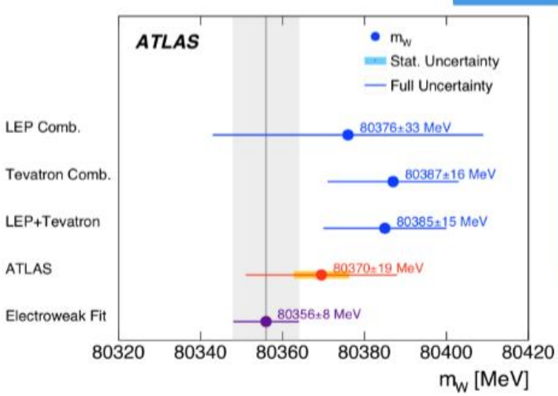
W Boson Mass

- Uses 4.6/fb of 7 TeV data
- Understanding detector response and modelling of kinematic variables critical
- Similar precision to best previous single experiment measurement (from CDF)
- Allows full test of SM consistency
- Further progress requires improved modelling

m_W = 80.370 ± 0.019 GeV
[± 7 MeV (stat.) ± 11 MeV (syst.) ± 14 MeV (modelling)]

arXiv:1701.07240
accepted by EPJC





Thanks to the experience gained with

Automation of NLO QCD+EW

$$\sigma^{\rm NLO} = \boxed{\int d\Phi_B (B + V + I) + \int d\Phi_R (R - S)}$$

OpenLoops

[JML, Maierhöfer, Pozzorini]

Sherpa

[Gleisberg, Höche, Krauss, Schönherr, Schumann, Siegert, Winter et. al.]

MUNICH:

MUlti-chaNnel Integrator at swiss (CH) precision

[Kallweit]

POWHEG-BOX

[Alioli, Nason, Oleari, Re, et. al.]

Herwig++/Matchbox

[Bellm, Gieseke, Grellscheid, Papaefstathiou, Plätzer, Richardson, Seymour, Siodmok et al.]

Whizard

[Kilian, Ohl, Reuter et. al.]

- NLO corrections in the full SM (QCD & EW) are implemented in OpenLoops+Sherpa/MUNICH
- missing: NLO EW + PS matching & merging (work in progress, approximation available!)
- **Automation allows for detailed phenomenological applications!**