SEARCHES FOR NEW PHYSICS IN CMS: FROM PHENO TO AMPLITUDES

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CMS

AMPHE2018 Workshop

Mainz, Germany, 20/8/2018

From Pheno to Amplitudes

- Not a typical search talk (but I could give one!)
- Rather than impressing you with a shopping list of all the searches we do, I'll focus on a very few, which I'll use as the examples of where theoretical progress either already made difference, or would be very helpful
- The examples I picked are mainly related to the topics of this workshop, albeit there are many other interesting theoretical issues related to searches (jet substructure and Sudakov logs, inclusive b quark production and FONLL, quarkonia polarization puzzle, etc.), which I'll skip
- Mainly use CMS examples; in most cases similar conclusions apply to ATLAS data as well

Monojets: the Classics

Monojet Searches

- Monojet analysis is a classical search for a number of new physics phenomena
  - Smoking gun signature for supersymmetry, large extra dimensions, dark matter production, ...
  - Was pursued since early 1980s
- The signature is deceptively simple, yet it's not
  - Backgrounds from instrumental effects
  - Irreducible $Z(\nu\nu)$+jet background
  - Reducible backgrounds from jet mismeasurements and W+jets with a lost lepton
- Number of techniques have been developed since the first search by UA1; will show the state-of-the-art results from CMS

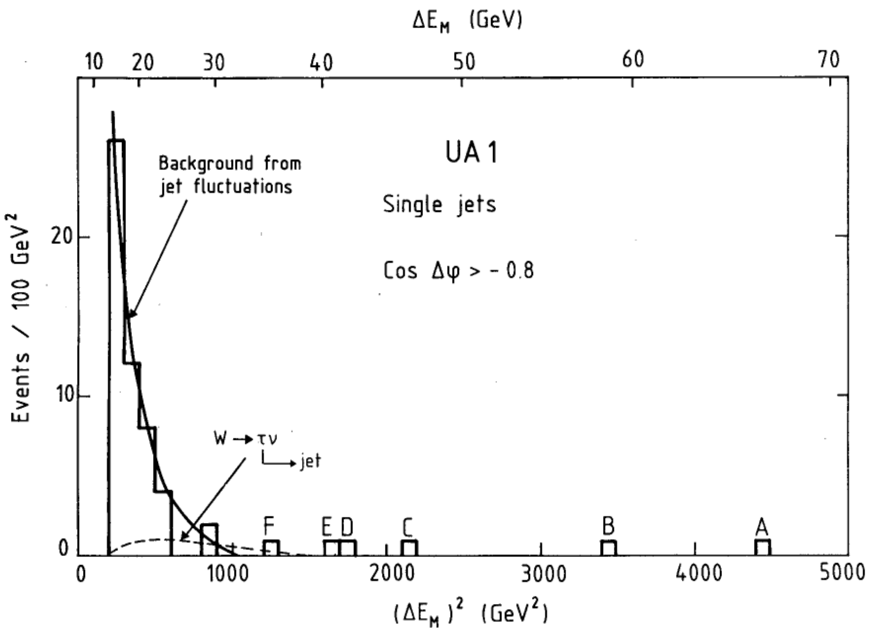
Monojet Searches

✦ We've come a long way since Carlo Rubbia's first attempt!

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON(S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

[PL, **139B**, 115 (1984)]

UA1 Collaboration, CERN, Geneva, Switzerland



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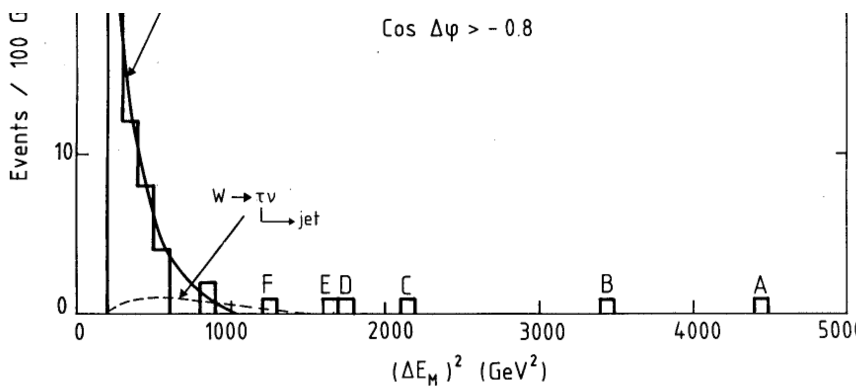

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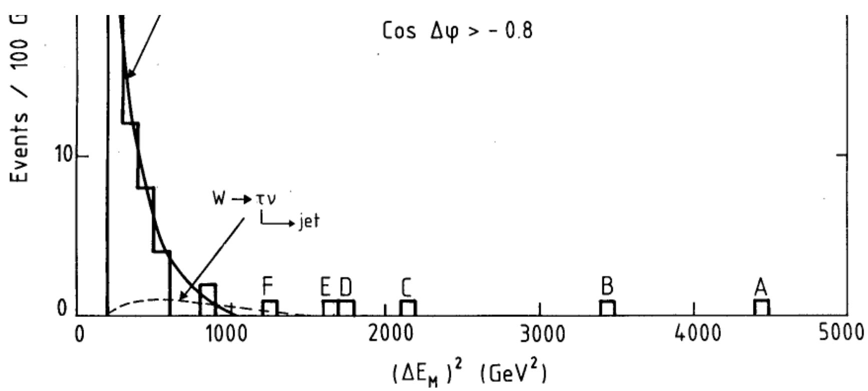
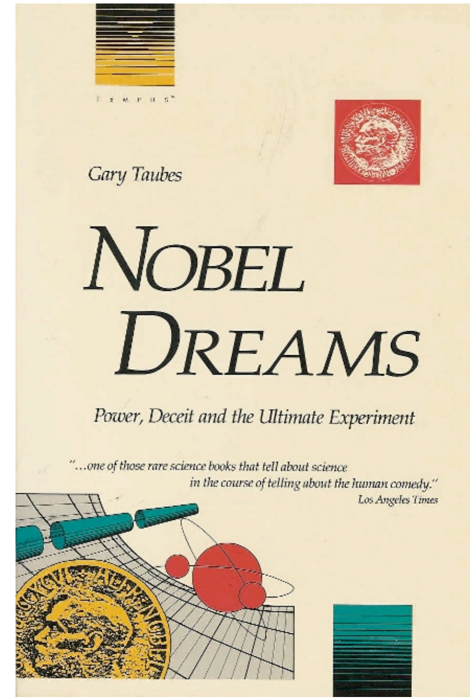
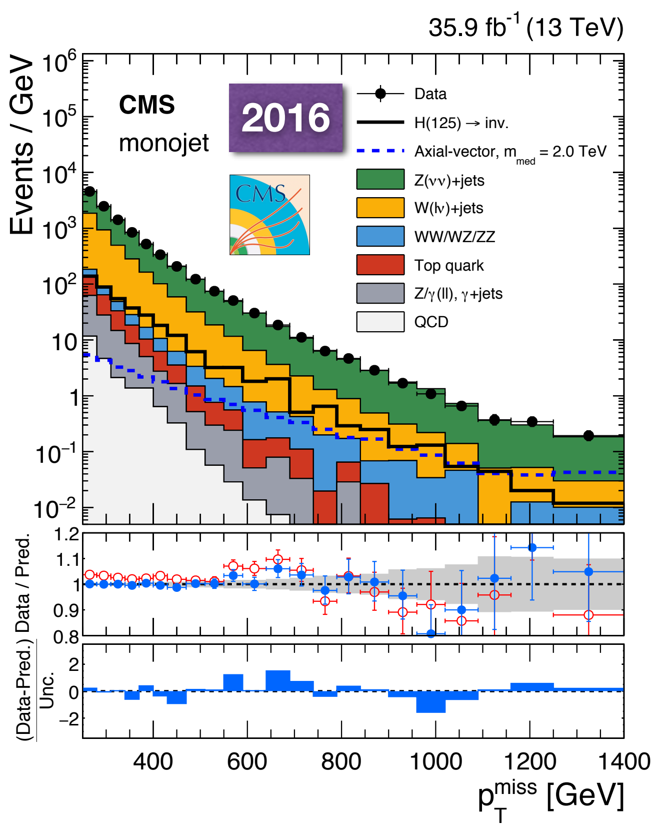


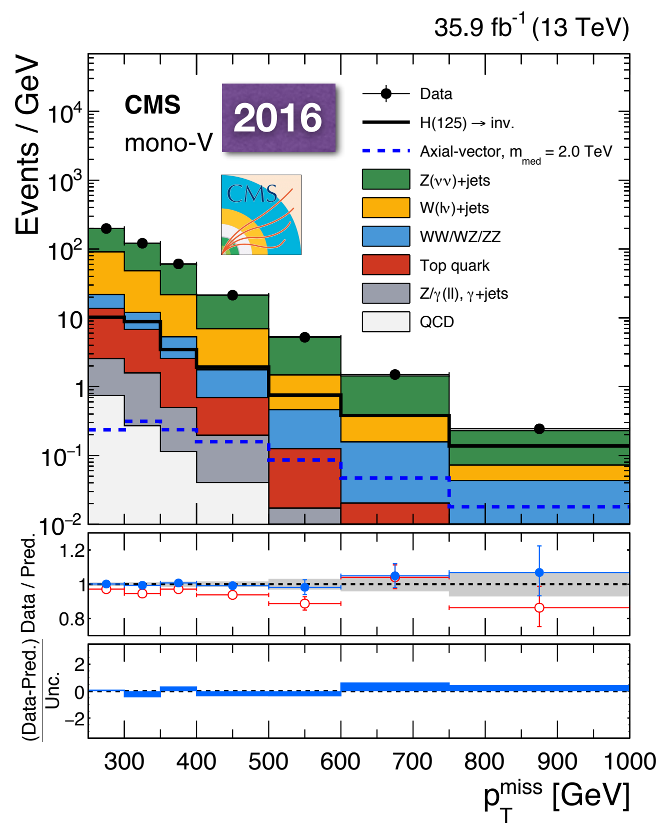


CMS Monojet Analysis

- The latest Run 2 analysis is built on the Run 1 techniques
  - Increased number of control regions (added e+jets, ee+jets)
  - Theoretically consistent treatment of EW/QCD corrections to SM V+jets processes, after Lindert et al., arXiv:1705.04464

CMS arXiv:1712.02345





DM Interpretation

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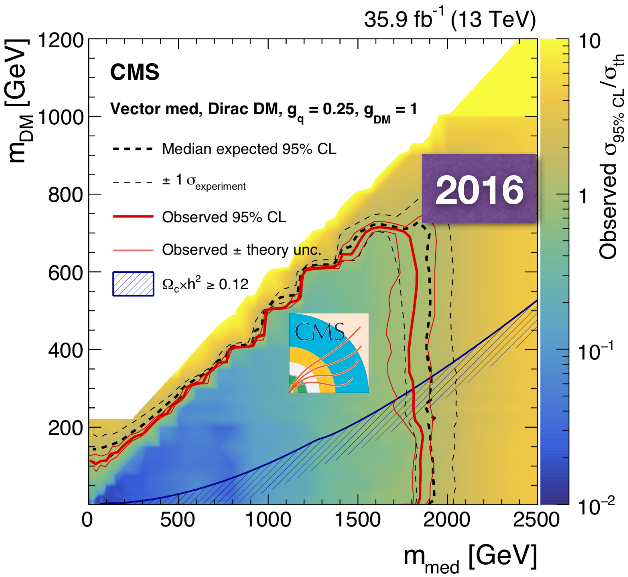
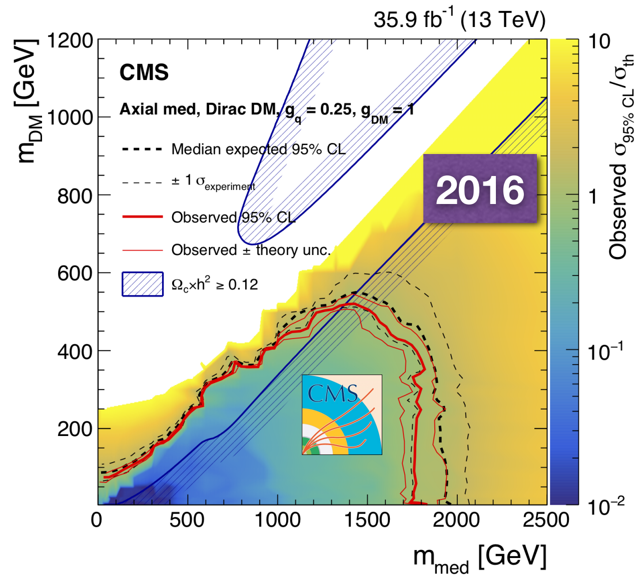
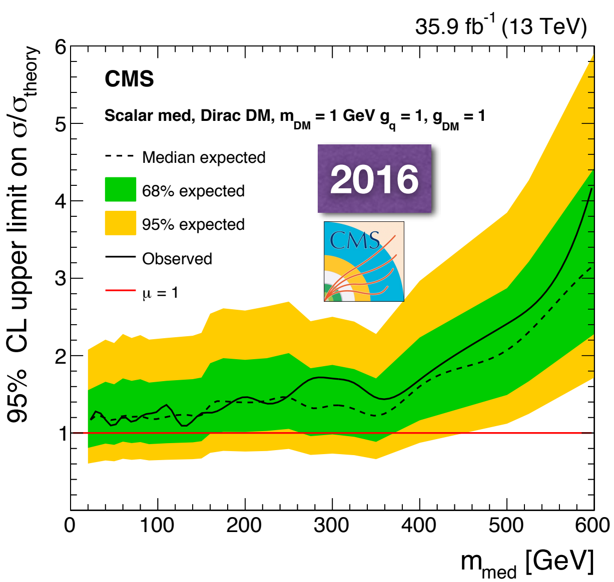
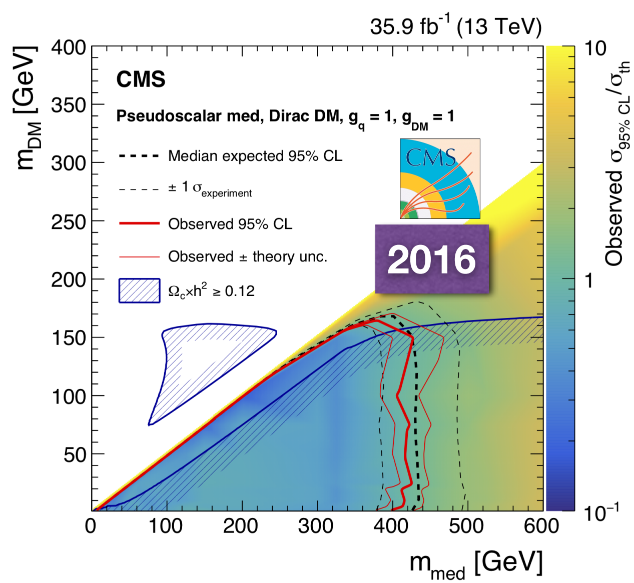






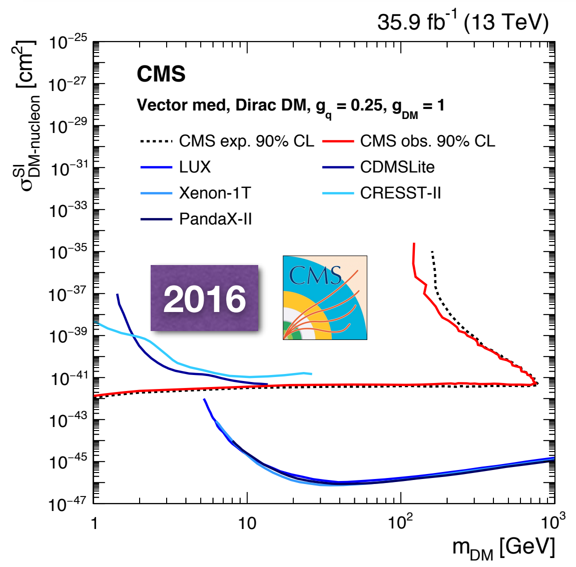


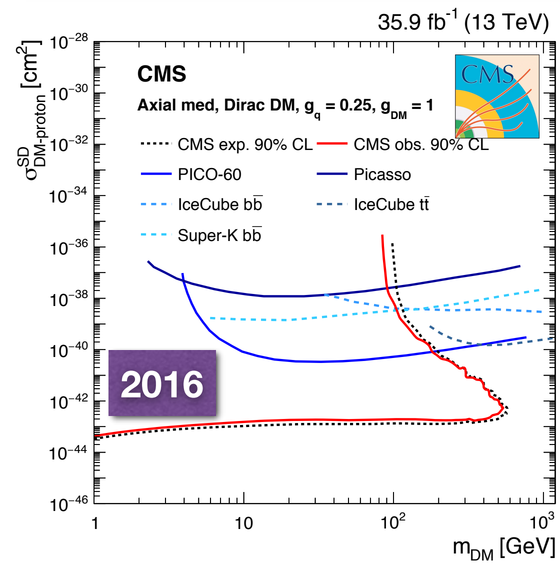
Fully compliant w/ LHC DM WG [arXiv:1603.04156] recommendations

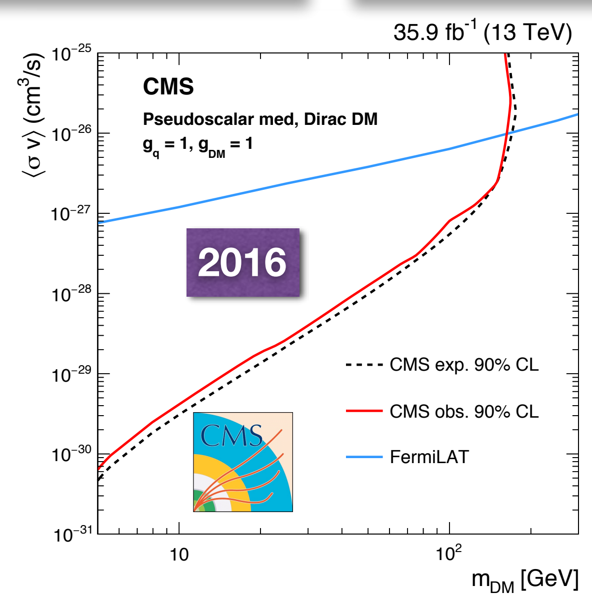
CMS arXiv:1712.02345

Comparison w/ I/DD

CMS arXiv:1712.02345

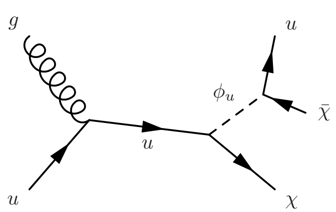


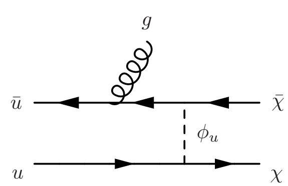


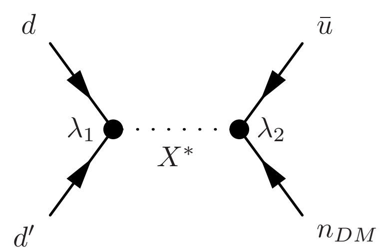


Other Interpretations

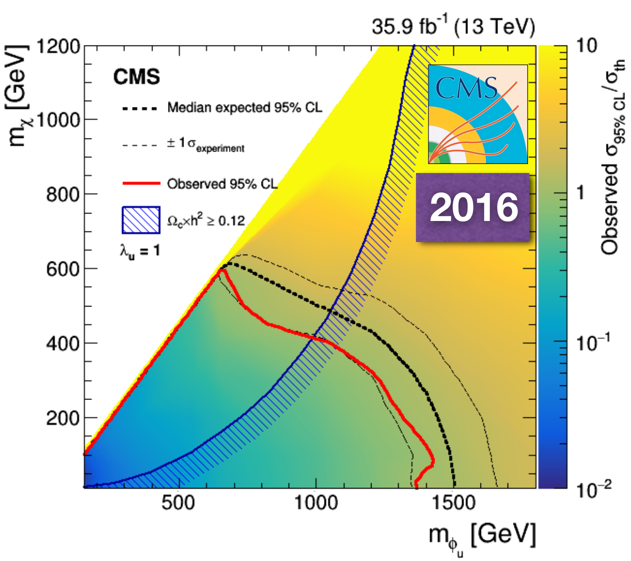
✦ Also sets limits on Dirac fermion [Bai/Berger, arXiv:1308.0612] and non-thermal [Dutta/Gao/Kamon, arXiv:1401.1825] DM models, as well as new limits on models with large extra dimensions

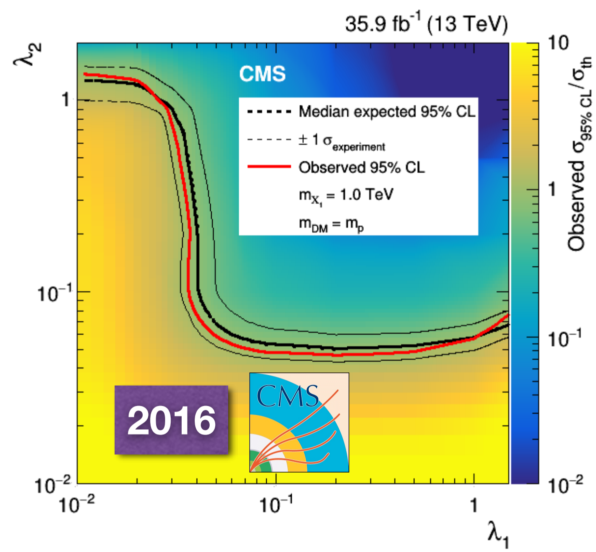


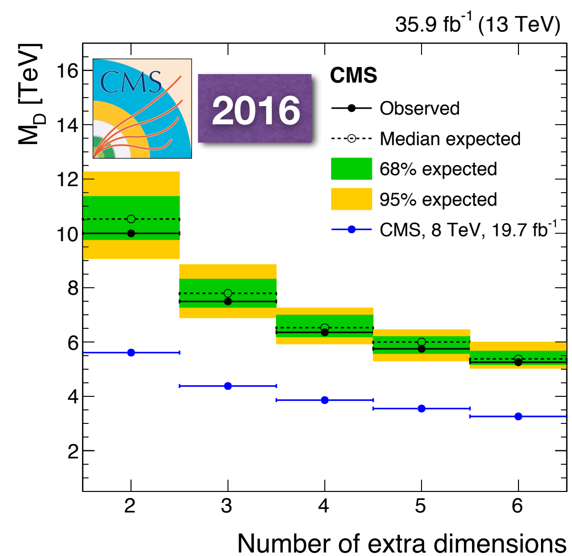




CMS arXiv:1712.02345







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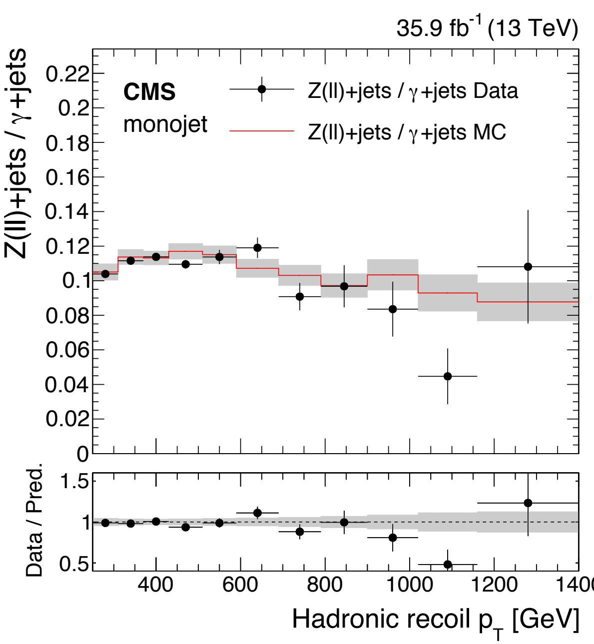
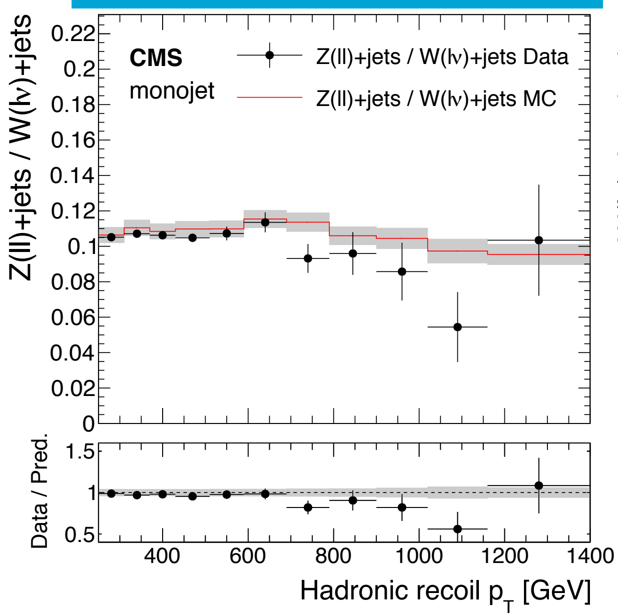
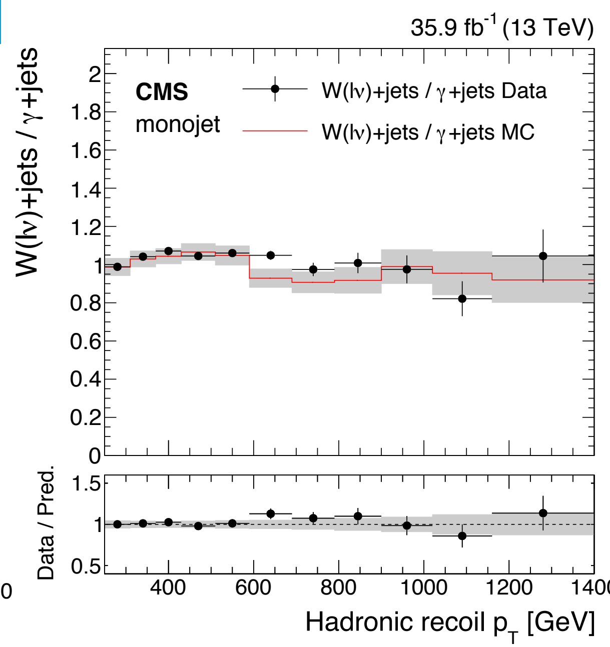
Anatomy of the Analysis

- In order to estimate the dominant Z(νν)+jets background with best precision, CMS employs 5 control regions (CRs) for each signal region (SR), "monojet" or "mono-V":
    - e/μ+jets CRs
    - ee/μμ+jets CRs
    - γ+jets CR
- The signal is extracted via simultaneous fit to the ME_T distribution in a given SR and to the hadronic recoil (proxy for ME_T) distribution in all the corresponding CRs
- The interplay between the CRs and SR is parameterized via transfer factors, determined from simulation

CMS arXiv:1712.02345



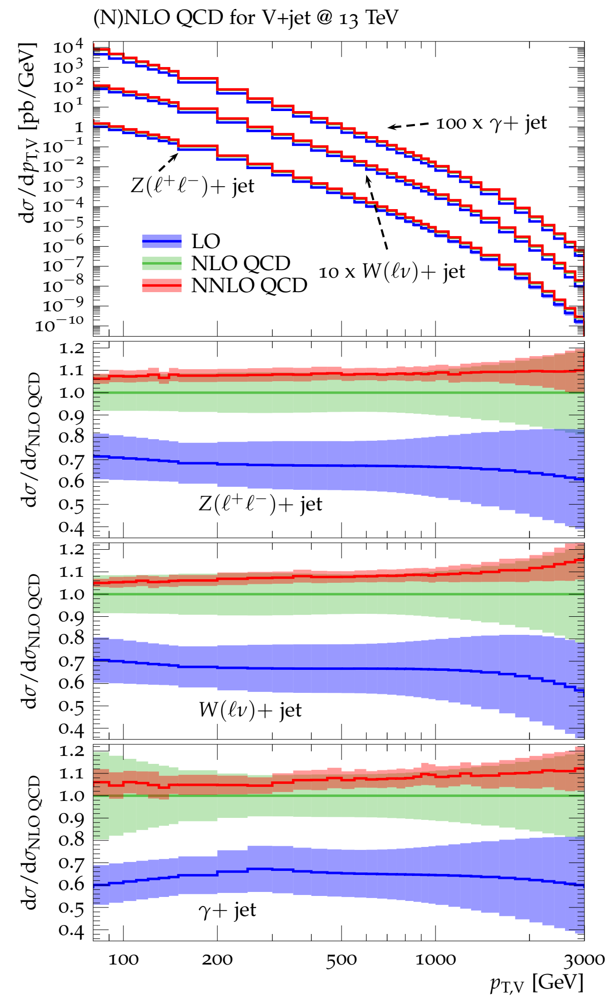




The Role of Theory

- The reason data and simulation agree so well is the state-of-the art EW and QCD NLO corrections used for V+jets simulations, as well as improved analysis of related uncertainties
- Based on the following recommendations:
  - Lindert et al, arXiv:1705.04664
  - See Refs. therein for individual calculations
- NLO QCD corrections:
  - Renormalization/factorization scale uncertainty [underestimate shape uncertainties]
  - Supplemented by altered boson p_T spectrum as an additional shape uncertainty to connect low- and high-p_T ranges
  - Additional uncertainty for the difference between γ+jets and W/Z+jets spectra

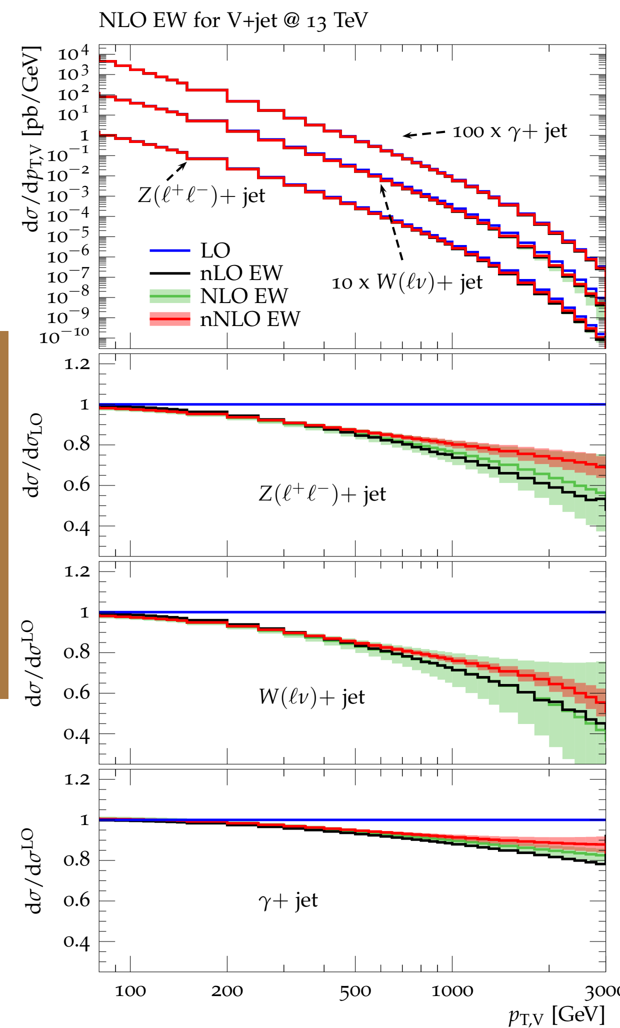
arXiv:1705.04664



The Role of Theory (cont'd)

- Next, EW corrections are included at NLO + two-loop Sudakov logs [Denner et al., arXiv:0906.1656, 1103.0914, 1211.5078; and Kallweit et al., arXiv:1511.08692]
- Again three uncertainties are considered:
  - EW from Sudakov logs beyond two loops (Sudakov exponentiation)
  - A 5% uncertainty in EW NLO K-factor to cover missing higher-order corrections
  - Third uncertainty to cover the difference between full NLL Sudakov log effects and naive EW NLO exponentiation

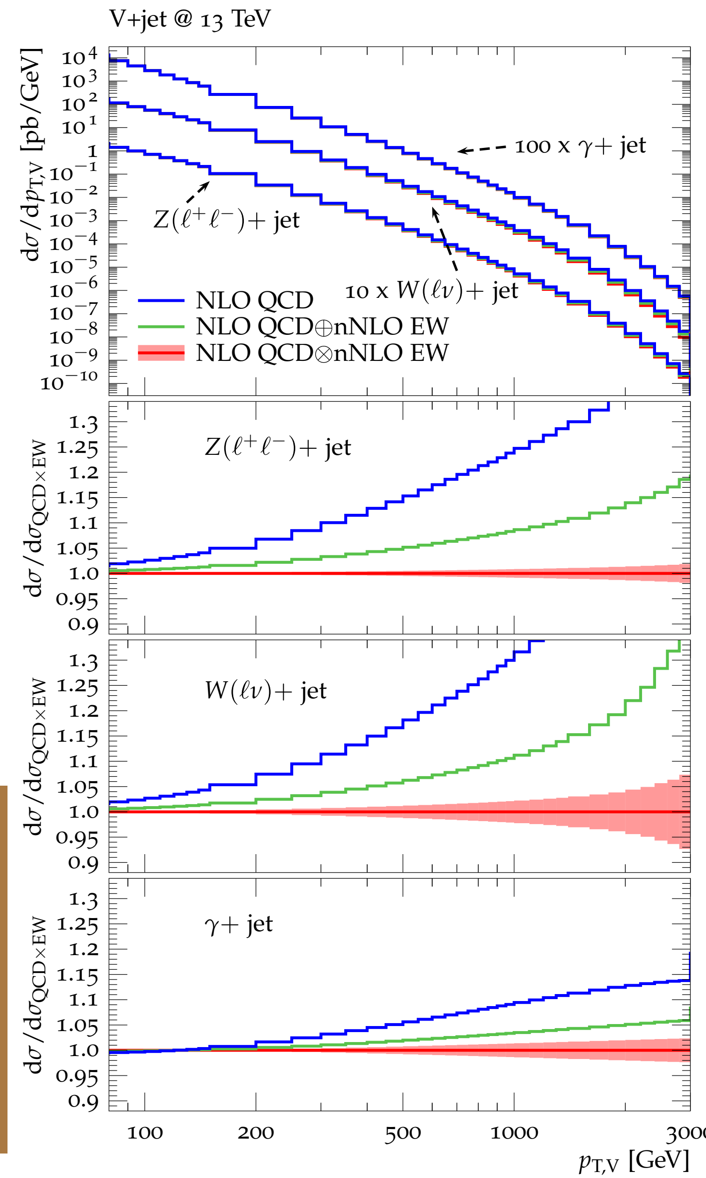
arXiv:1705.04664



The Role of Theory (cont'd)

- Next, there are several approaches how to combine NLO QCD and EW corrections
- Use a factorized approach, which partially includes mixed QCD-EW corrections
  - Covered by an extra uncertainty for the difference between the additive and multiplicative approaches
- Finally, include the PDF uncertainties

arXiv:1705.04664



Summary of Theory Uncertainties

CMS arXiv:1712.02345

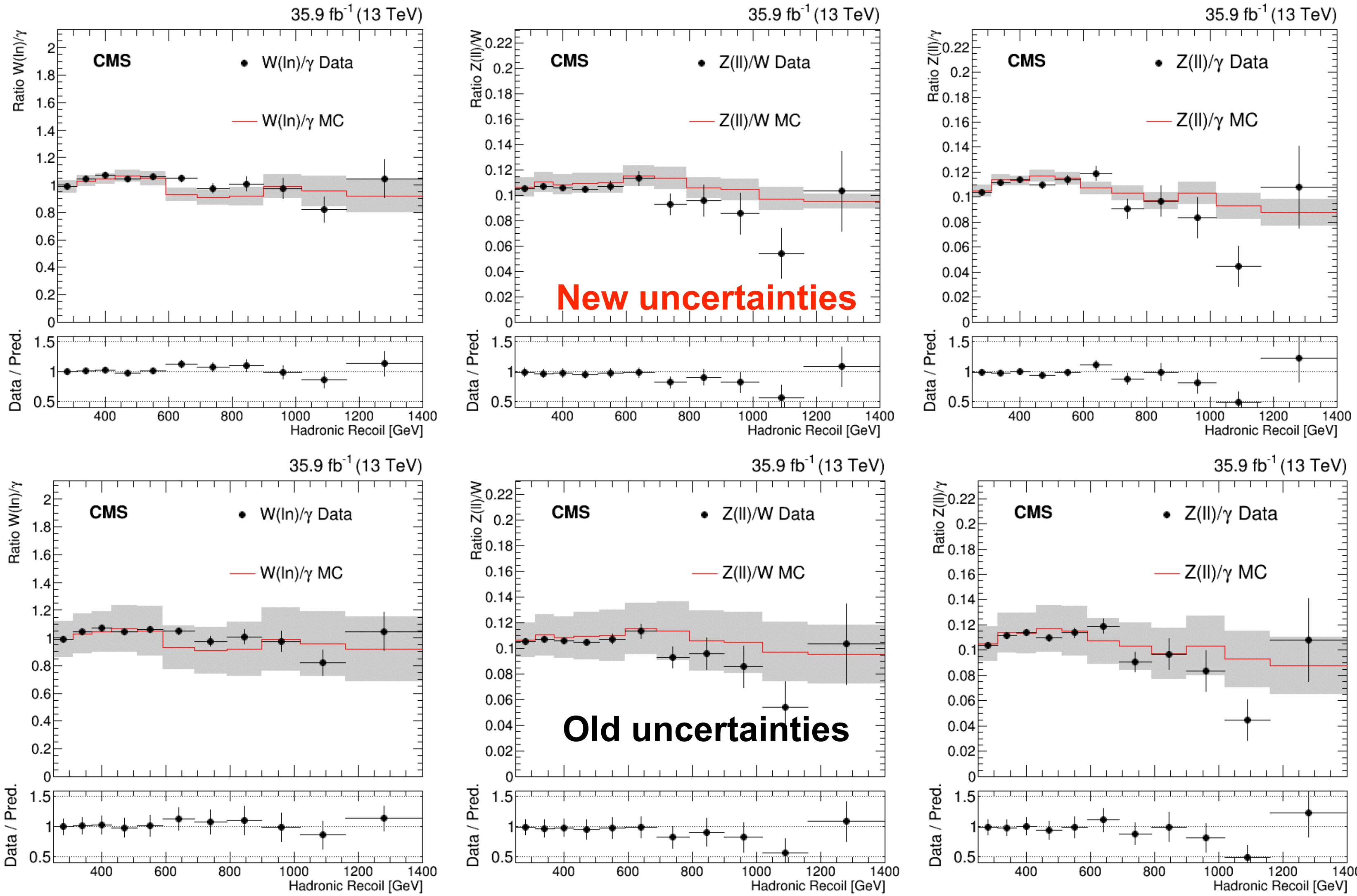
- Final theory uncertainties
  - Significant improvement over previous versions of the analysis, which was based on less precise calculations

Uncertainty source	Process (magnitude)	Correlation
Fact. & renorm. scales (QCD)	$Z \to \nu\nu / W \to \ell\nu$ (0.1 – 0.5%) $Z \to \nu\nu / \gamma$+jets (0.2 – 0.5%)	Correlated between processes; and in p_T
p_T shape dependence (QCD)	$Z \to \nu\nu / W \to \ell\nu$ (0.4 – 0.1%) $Z \to \nu\nu / \gamma$+jets (0.1 – 0.2%)	Correlated between processes; and in p_T
Process dependence (QCD)	$Z \to \nu\nu / W \to \ell\nu$ (0.4 – 1.5%) $Z \to \nu\nu / \gamma$+jets (1.5 – 3.0%)	Correlated between processes; and in p_T
Effects of unknown Sudakov logs (EW)	$Z \to \nu\nu / W \to \ell\nu$ (0 – 0.5%) $Z \to \nu\nu / \gamma$+jets (0.1 – 1.5%)	Correlated between processes; and in p_T
Missing NNLO effects (EW)	$Z \to \nu\nu$ (0.2 – 3.0%) $W \to \ell\nu$ (0.4 – 4.5%) γ+jets (0.1 – 1.0%)	Uncorrelated between processes; correlated in p_T
Effects of NLL Sudakov approx. (EW)	$Z \to \nu\nu$ (0.2 – 4.0%) $W \to \ell\nu$ (0 – 1.0%) γ+jets (0.1 – 3.0%)	Uncorrelated between processes; correlated in p_T
Unfactorized mixed QCD-EW corrections	$Z \to \nu\nu / W \to \ell\nu$ (0.15 – 0.3%) $Z \to \nu\nu / \gamma$+jets (<0.1%)	Correlated between processes; and in p_T
PDF	$Z \to \nu\nu / W \to \ell\nu$ (0 – 0.3%) $Z \to \nu\nu / \gamma$+jets (0 – 0.6%)	Correlated between processes; and in p_T

Comparison w/ Older Analyses

✦ The effect of reduced theoretical uncertainties:

CMS arXiv:1712.02345



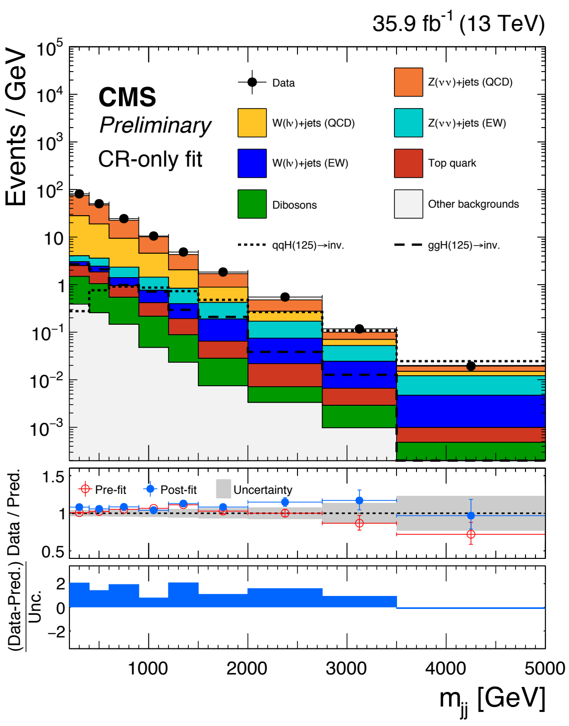
CMS arXiv:1703.01651-like

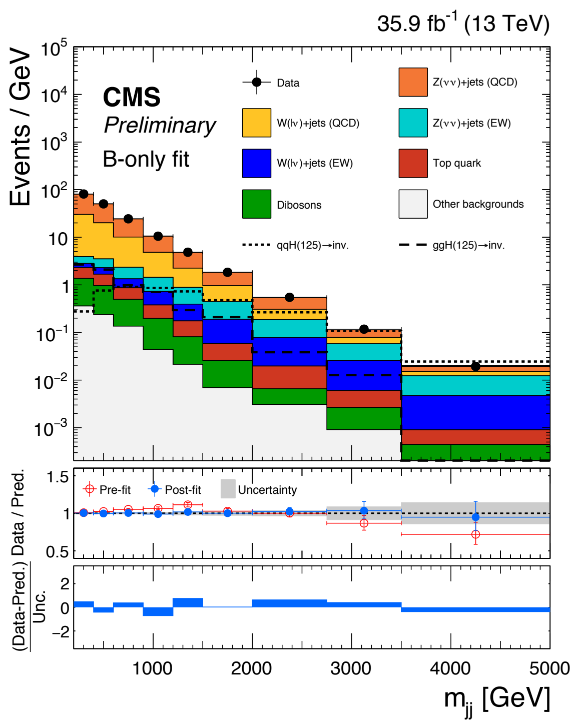
Experimenters' Wishlist

- I know it's simpler to say than to do, nevertheless:
  - We would like similar level of understanding for the V+b and V+bb production
    - This would benefit a lot bb+MET searches (SUSY, DM), such as mono-Higgs and generic mono-bb
  - We would also like to have similar connection well understood theoretically between Wγ, Zγ, and $\gamma\gamma$
    - This would benefit monophoton analysis the same way the monojets benefit from V+jets understanding
  - Finally, we would also like the understanding of EW V+jets production in the VBF phase space (including interference with QCD V+jets)
    - This would benefit measurement of EW production and qTGC, as well as H(inv.) searches (next slide)

Invisible Higgs Decay

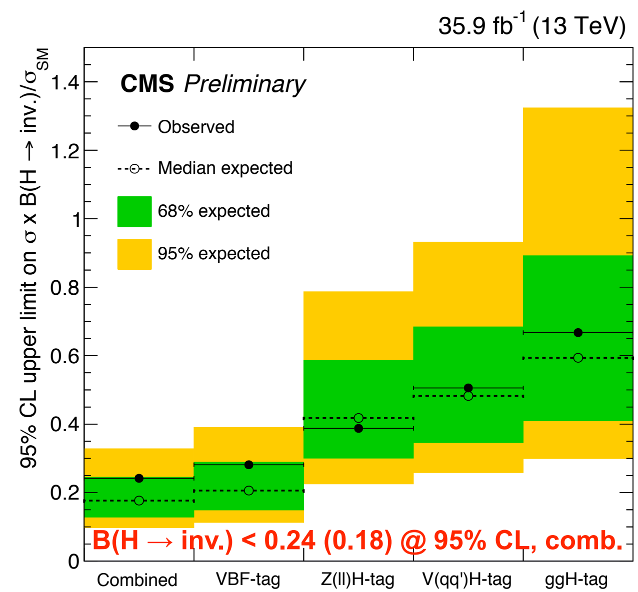
- ✦ New H(inv.) search based on VBF topology
- ✦ Similar approach to the monojet search, except requiring two forward jets and the lack of γ+jets CR; also no V+jets SR
- ✦ Use dijet mass as the sensitive variable
- ✦ Significantly larger transfer factor uncertainties than in monomers due to lack of theoretical calculations (EW V+jets only includes NLO QCD)





CMS PAS HIG-17-023

B(H → inv.) < 0.28 (0.21) @ 95% CL

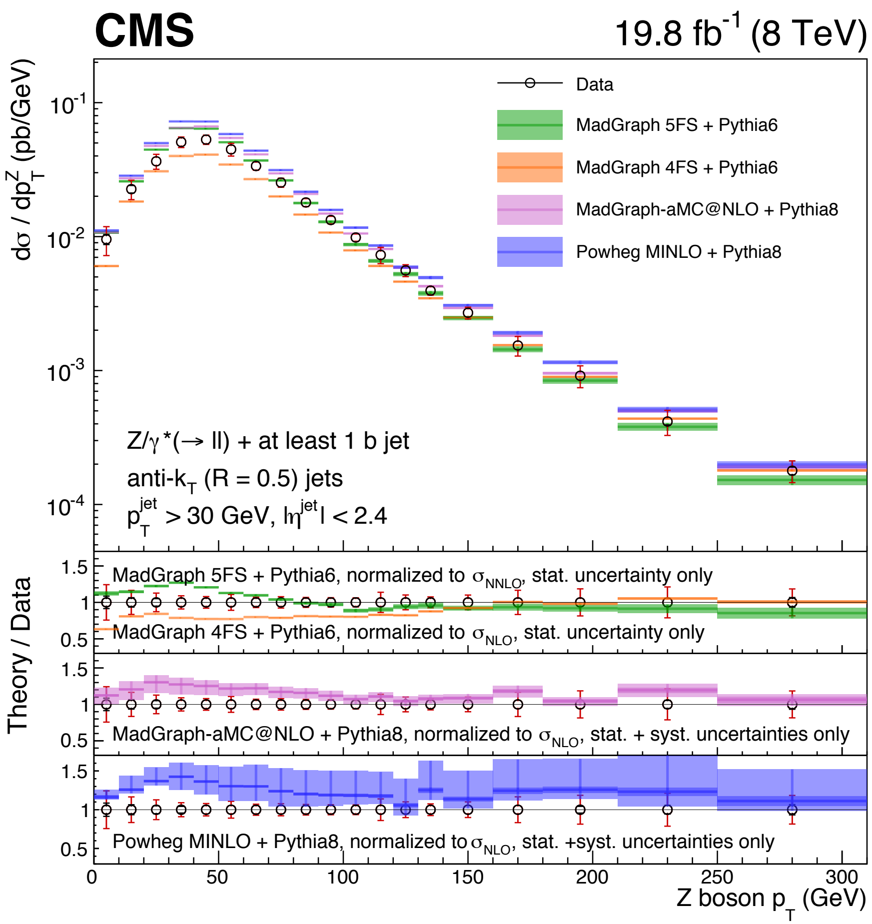


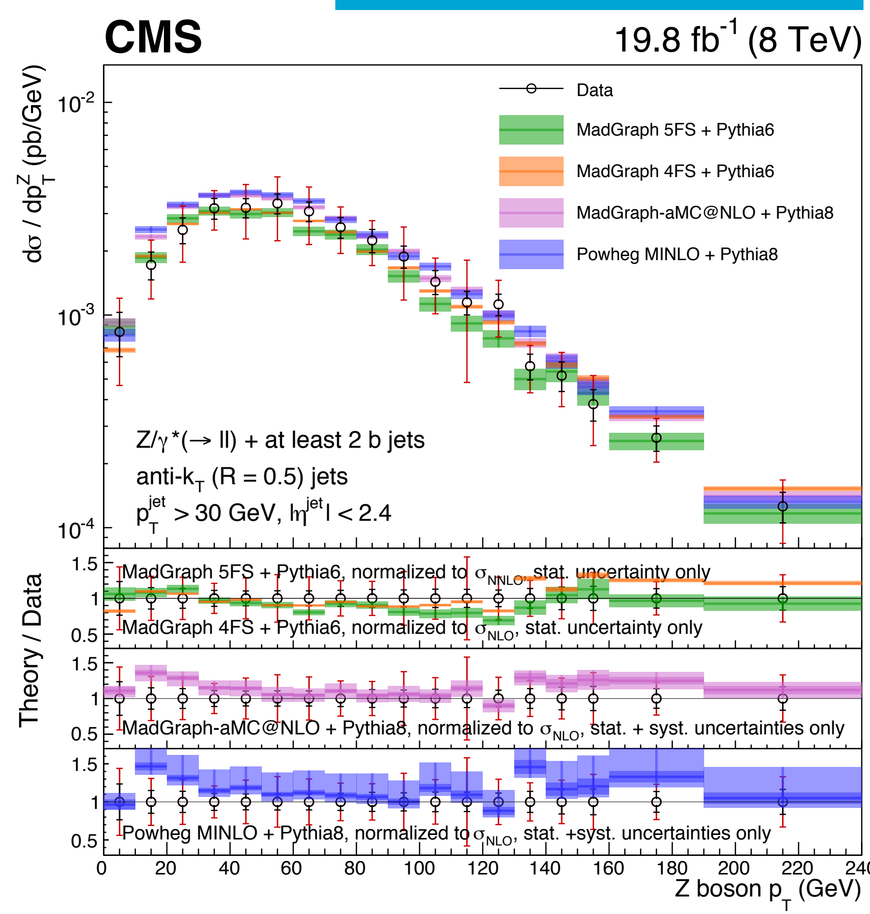
Z+b's Story

Z+b(b) Story

- ✦ Associated production of Z with one or two b jets have been measured to a high precision
- ✦ 5FS LO+PS and NLO+PS predictions generally reproduce inclusive data, although differential distributions exhibit certain shape difference

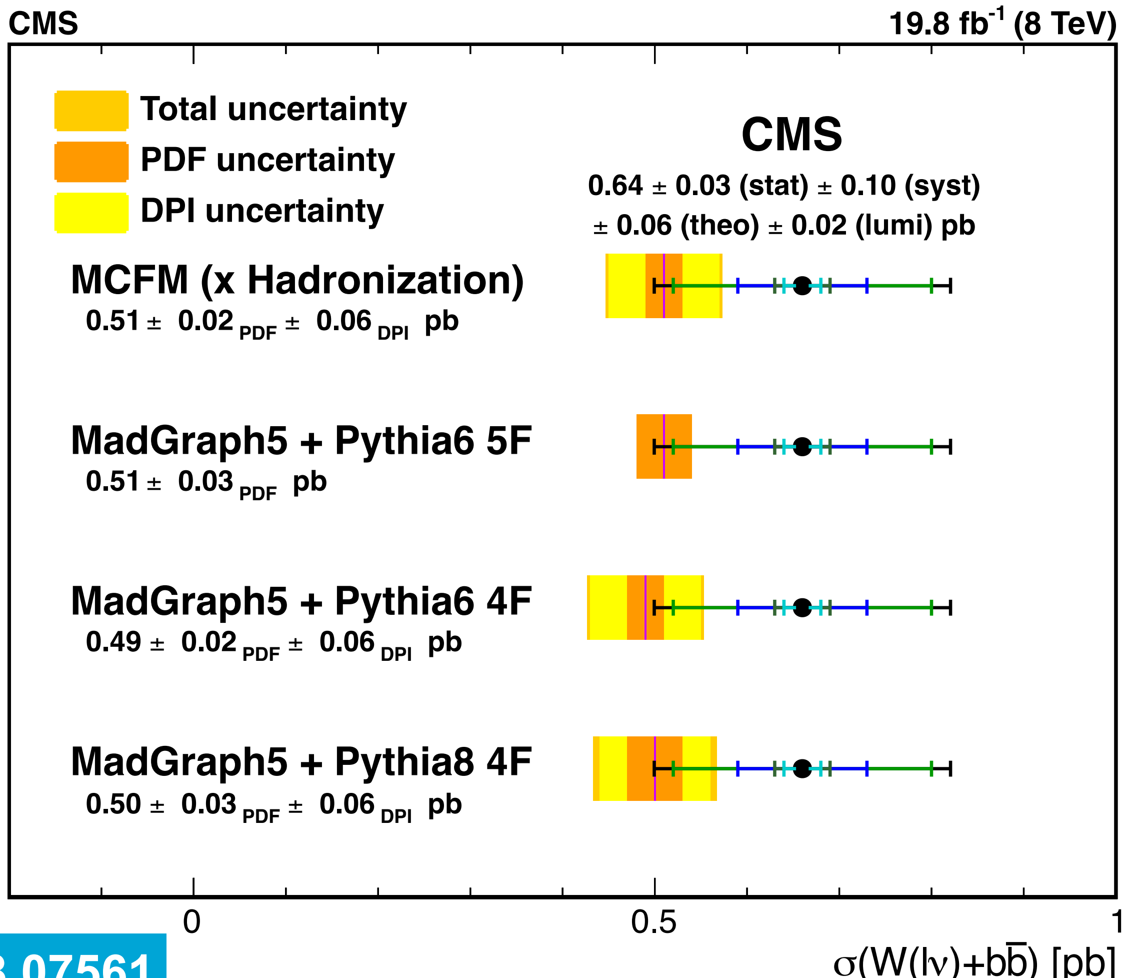
CMS arXiv:1611.06507





What about W+b(b)

- ✦ Here the data are inconclusive, as only an inclusive measurement exists, with ~20% precision



CMS arXiv:1608.07561

V+b(b) as VH(bb) Background

- However, in certain regions of the phase space, in particularly at high boson boost, typical for VH(bb) searches, the agreement is not good
  - It's clearly getting worse with increasing $p_T(V)$
- W+b(b) seems to follow the same trend
- Better theoretical understanding of this regime would be very useful

Process	0-lepton	1-lepton	2-lepton low-p_T(V)	2-lepton high-p_T(V)
W0b	1.14 ± 0.07	1.14 ± 0.07	—	—
W1b	1.66 ± 0.12	1.66 ± 0.12	—	—
W2b	1.49 ± 0.12	1.49 ± 0.12	—	—
Z0b	1.03 ± 0.07	—	1.01 ± 0.06	1.02 ± 0.06
Z1b	1.28 ± 0.17	—	0.98 ± 0.06	1.02 ± 0.11
Z2b	1.61 ± 0.10	—	1.09 ± 0.07	1.28 ± 0.09
$t\bar{t}$	0.78 ± 0.05	0.91 ± 0.03	1.00 ± 0.03	1.04 ± 0.05

CMS arXiv:1709.07497

Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.90 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	0.97 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	1.04 ± 0.06
W + HF 2-jet	1.22 ± 0.14
W + HF 3-jet	1.27 ± 0.14
Z + HF 2-jet	1.30 ± 0.10
Z + HF 3-jet	1.22 ± 0.09

ATLAS arXiv:1708.03299

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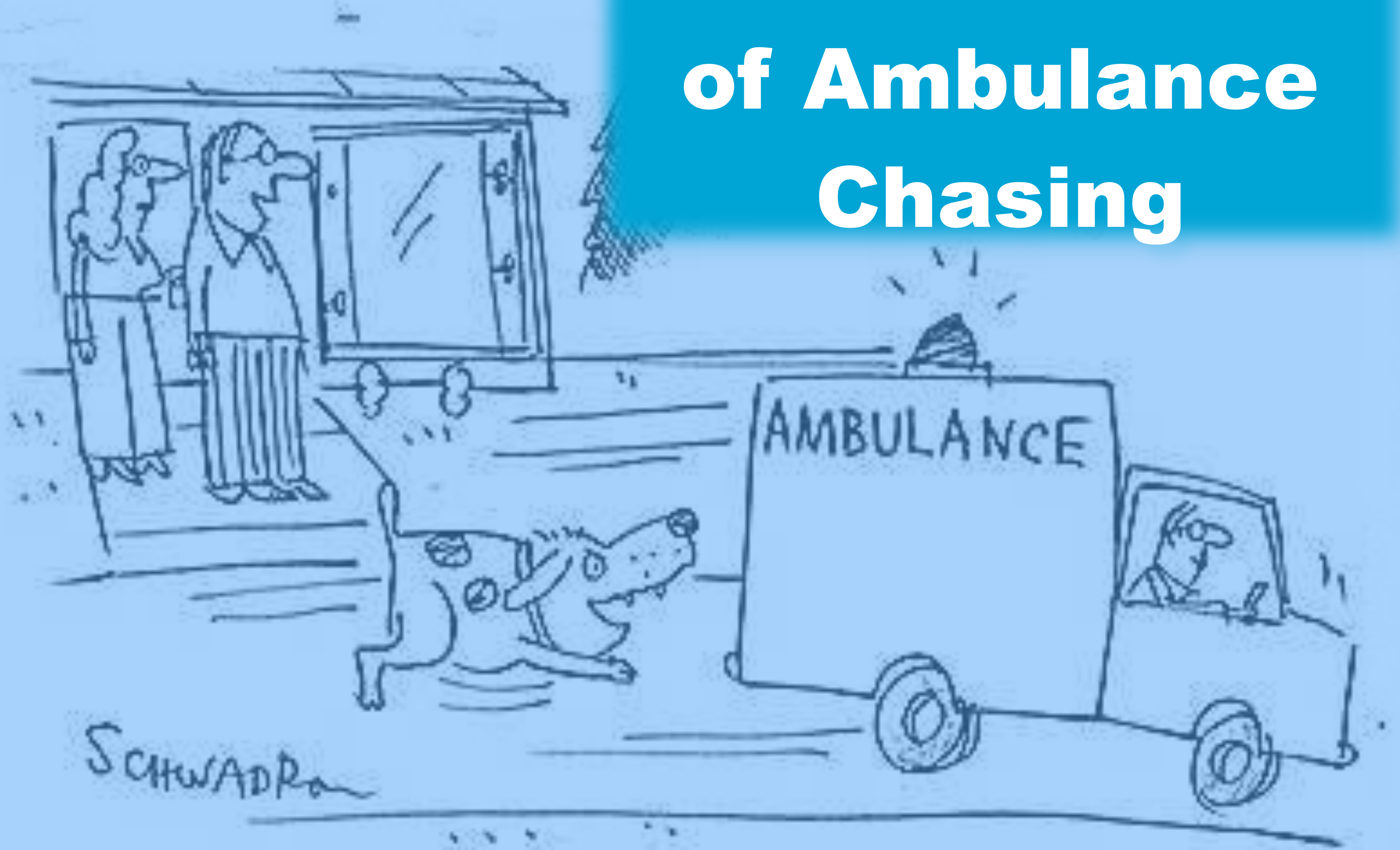
ATLAS arXiv:1708.03299

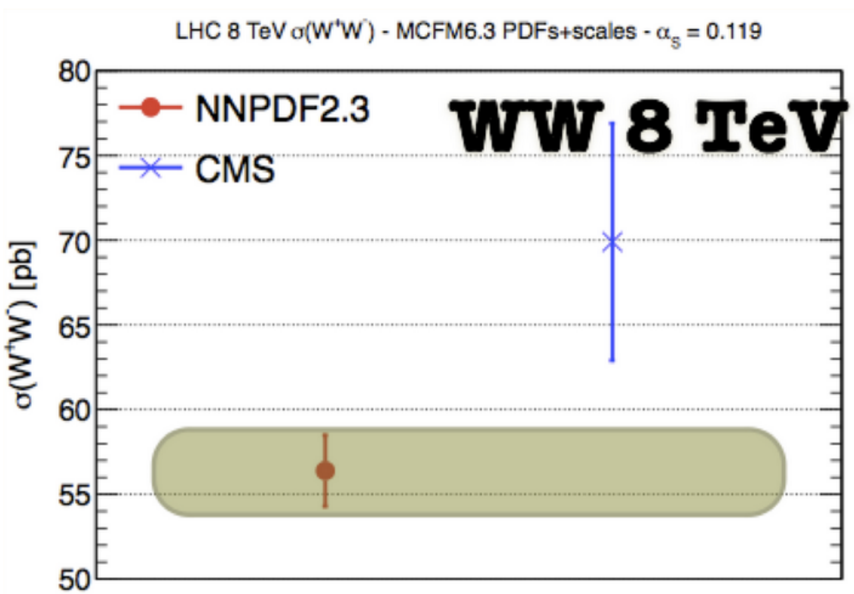
Standard Model of Ambulance Chasing

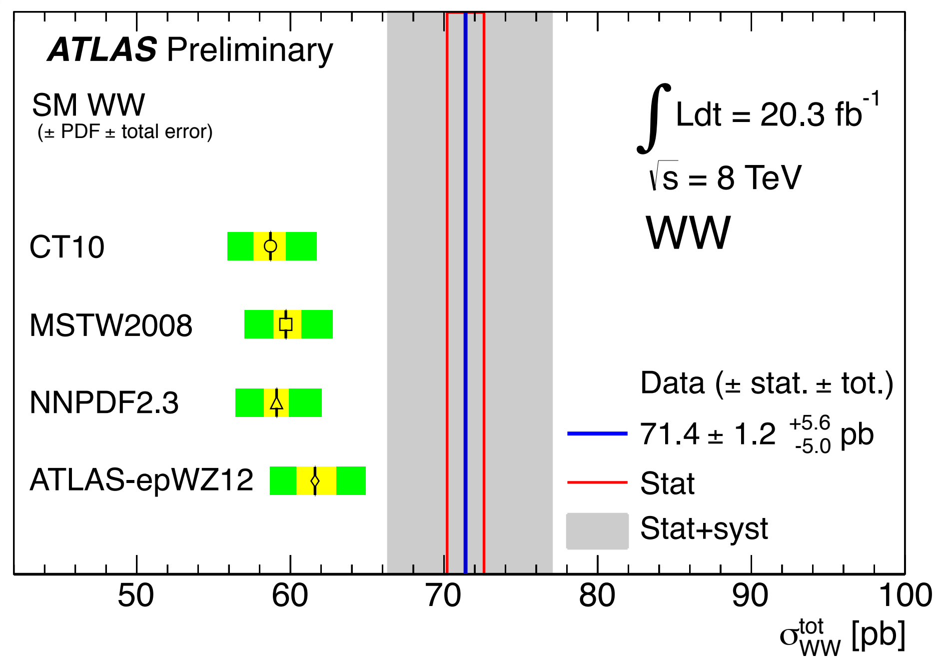


"He's in training for a career in law."

WW Cross Section (2014)

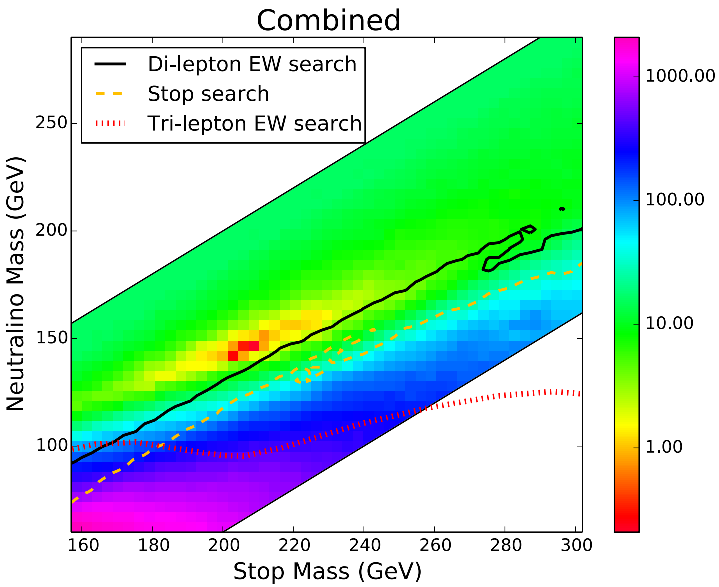
- Not a new subject, but illustrative as to the importance of precise theory predictions
- In 2012-2014, a ~2σ excess of WW production cross section w.r.t. NLO predictions was consistently observed by ATLAS and CMS at 7 and 8 TeV





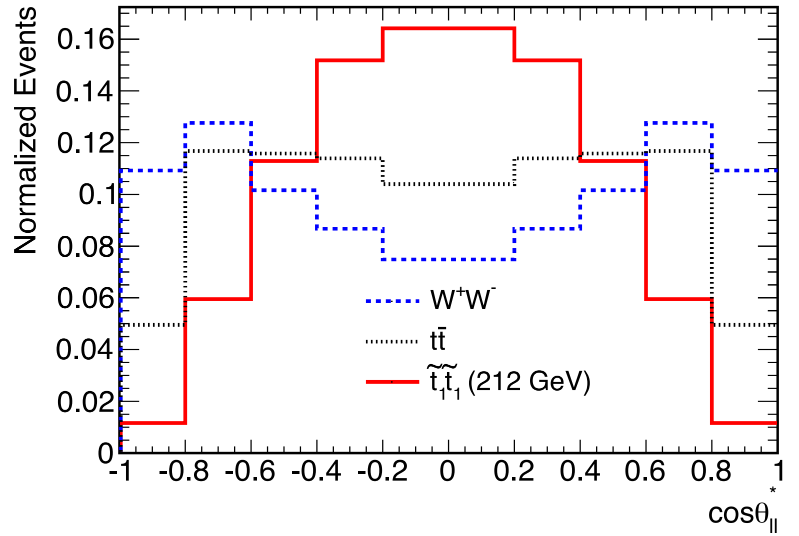
Ambulance Chasing

- Not much of an excess, but it triggered a round of ambulance chasing with proposals to explain it via light top squarks, charginos, sleptons, etc.
  - Curtin, Meade, Tien, arXiv:1406.0848
  - Kim, Rolbiecki, Sakurrai, Tattersall, arXiv:1406.0858
  - Luo, Luo, Xu, Zhu, arXiv:1407.4912
  - ...



arXiv:1406.0858

Importance of differential distributions



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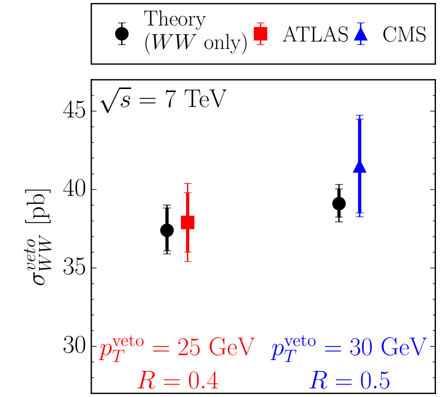
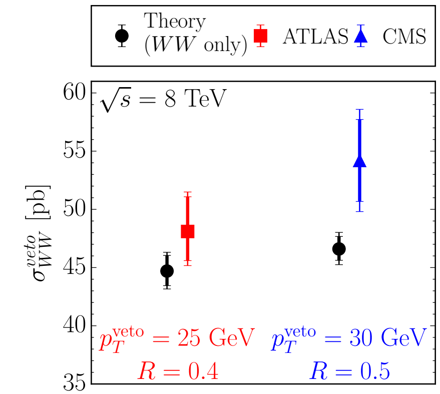
More Sober Approaches

- To their credit, not everyone left after the ambulance
- More sober proposed explanations for the observed excess included:
  - Jaiswall, Okui, arXiv:1407.4537 - large logs due to the effects of b-jet veto used to suppress the dominant tt background
    - Related work by Becher et al., arXiv:1412.8408
  - Monni, Zanderighi, arXiv:1410.4745 - noticed that fiducial cross section agrees well with theory; suggested that the discrepancy originates from extrapolation to the full phase space, where K-factors could be large (cf. amplitude zero in WW)



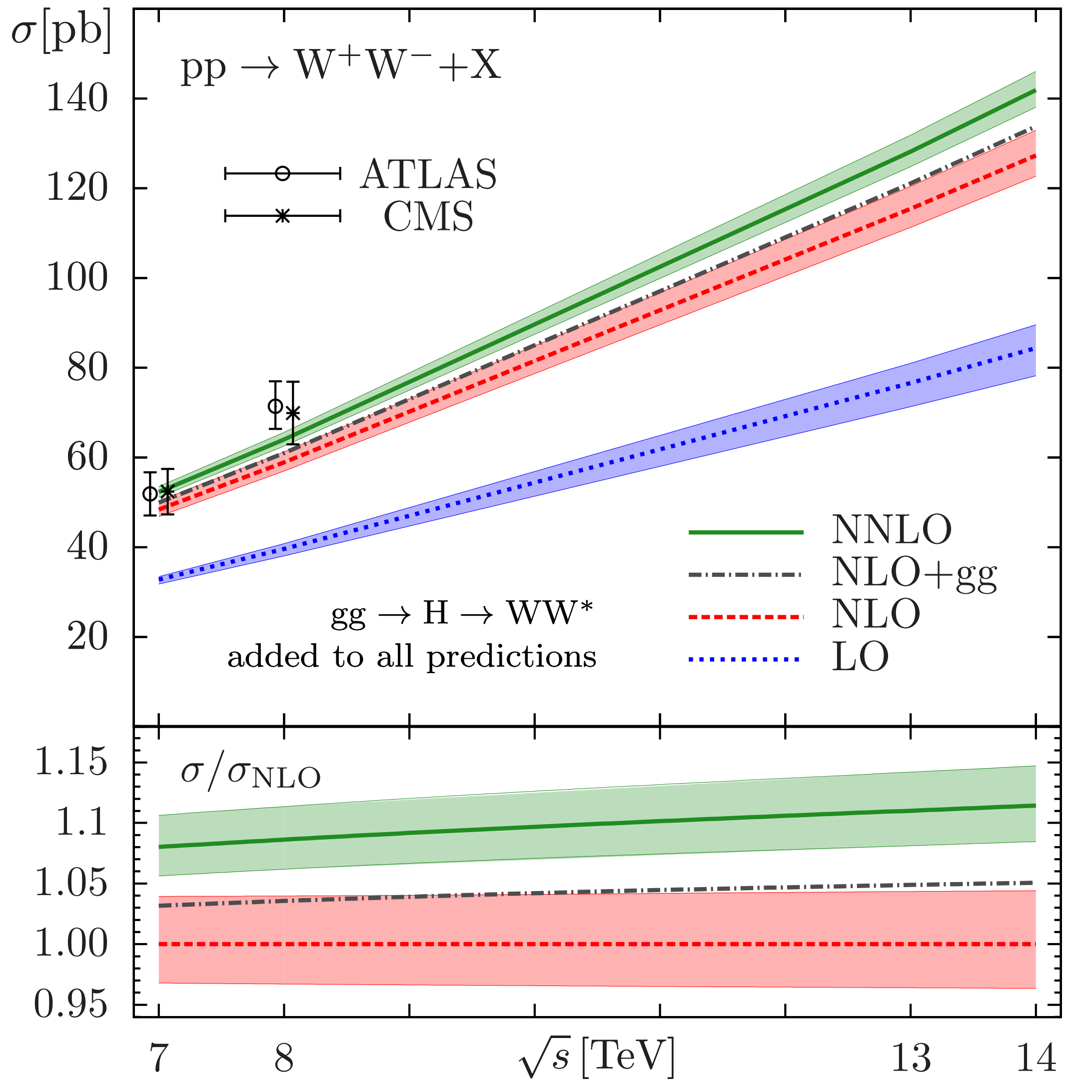
arXiv:1407.4537



NNLO To Rescue

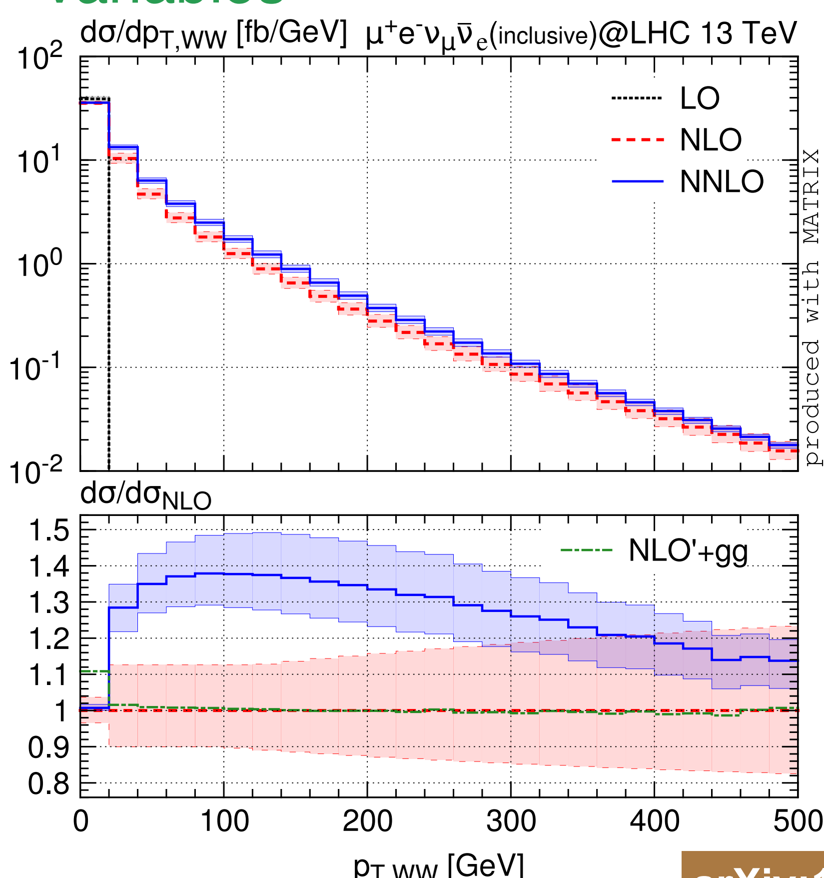
- Soon, the puzzle was resolved via full NNLO calculations by Gehrmann et al., arXiv:1408.5243
- They showed that NNLO effects are significant (O(10%)) and largely cure the discrepancy with the experimental data

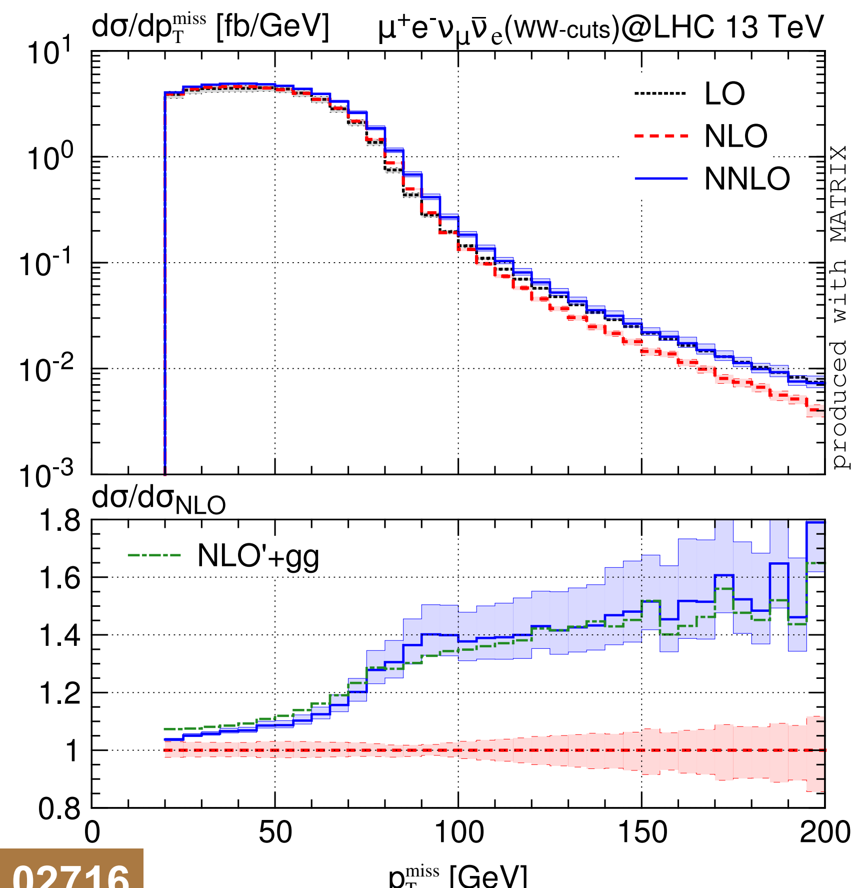
arXiv:1408.5243



Differential Cross Sections

- A follow-up paper by largely the same group of authors [Grazzini et al., arXiv:1605.02716] showed that NNLO corrections could lead to substantial changes in the shape of WW kinematic variables

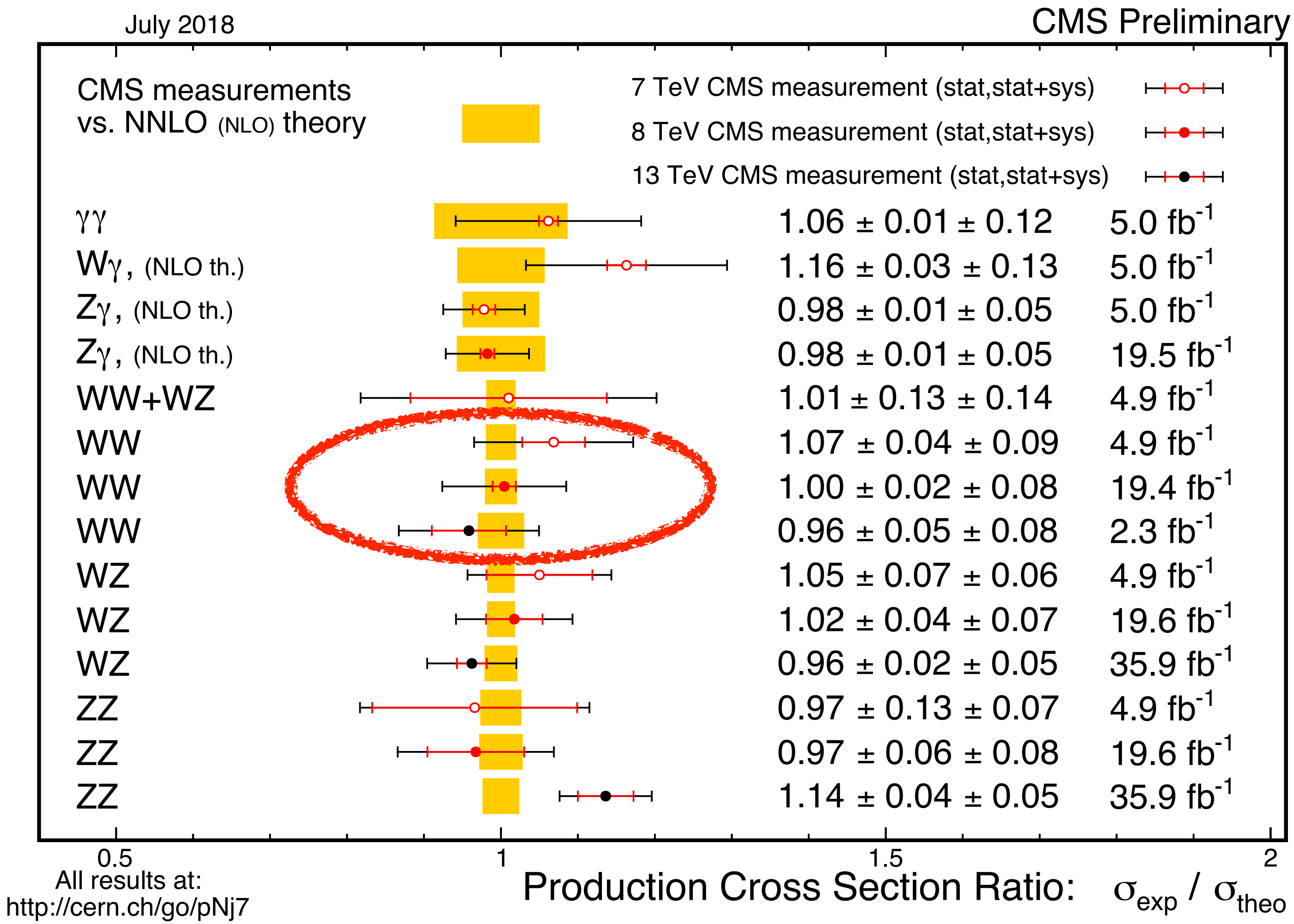




arXiv:1605.02716

After the Dust Settled

- ✦ Recent measurements are in excellent agreement with the NNLO predictions



Lessons Learned

- Insufficient precision of theoretical predictions is a fruitful ground for ambulance chasers
- The community has long became "trigger-happy" to explain any 2σ-ish deviation with new physics
- Extrapolation to full phase space is often a dangerous step with the uncertainties hard to control
    - Fiducial cross sections should always be reported by the experiments, in addition
- Higher-order calculations could come to rescue
- Differential distributions calculated at higher orders are of particular importance - we would like to see more of those available

Top pT Woes

Top Momentum

Real Estate

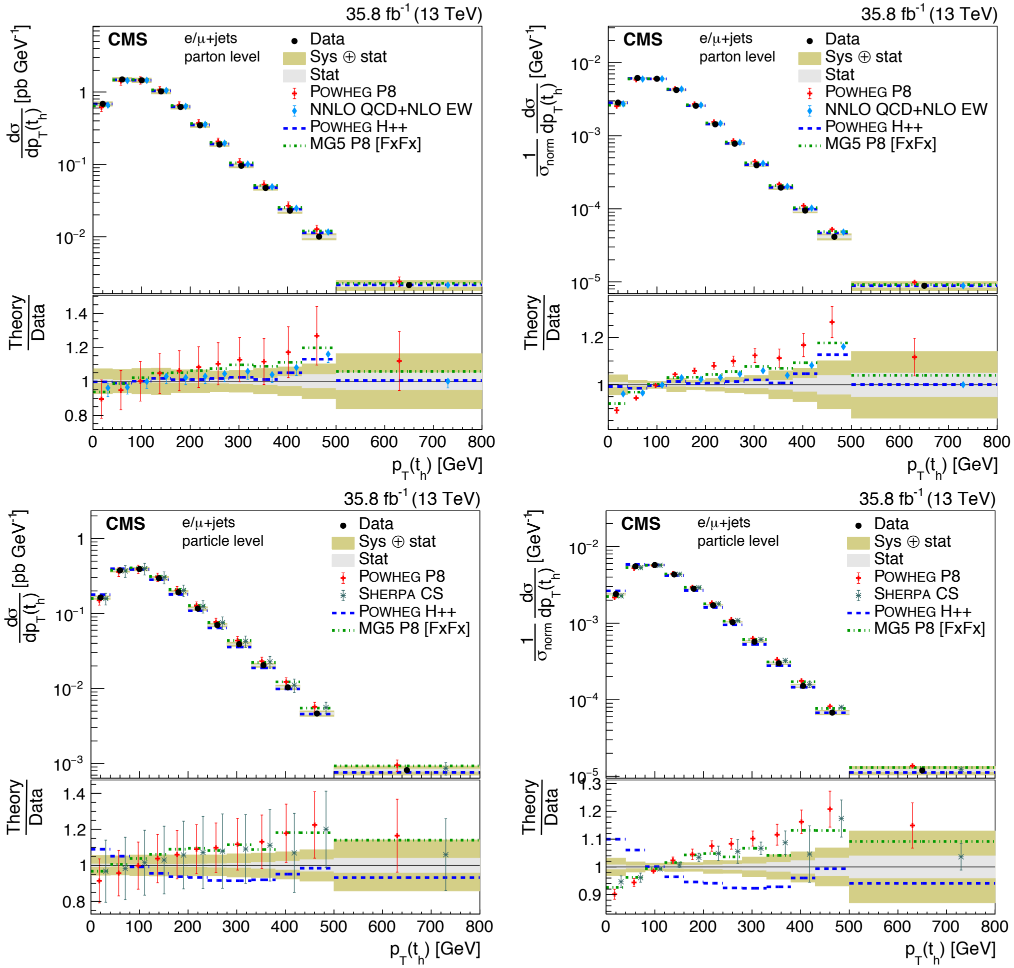
Top Quark p_T Spectrum

- The discrepancy between the NLO predictions and the data in top quark p_T spectrum in tt production have been a long-standing problem
- Observed with pretty much all the generator and poses a problem for many searches for new physics where one has to reweight the p_T spectrum to match the data, resulting in a ~10% additional uncertainty in the background prediction
- The agreement is a bit better with NNLO calculations (still not perfect!), but we lack NNLO generators capable of event generation
- Seen consistently at all collision energies in both ATLAS and CMS

Top Quark p_T Spectrum

- The discrepancy between the NLO predictions and the data in top quark p_T spectrum in tt production have been a long-standing problem

CMS arXiv:1803.08856



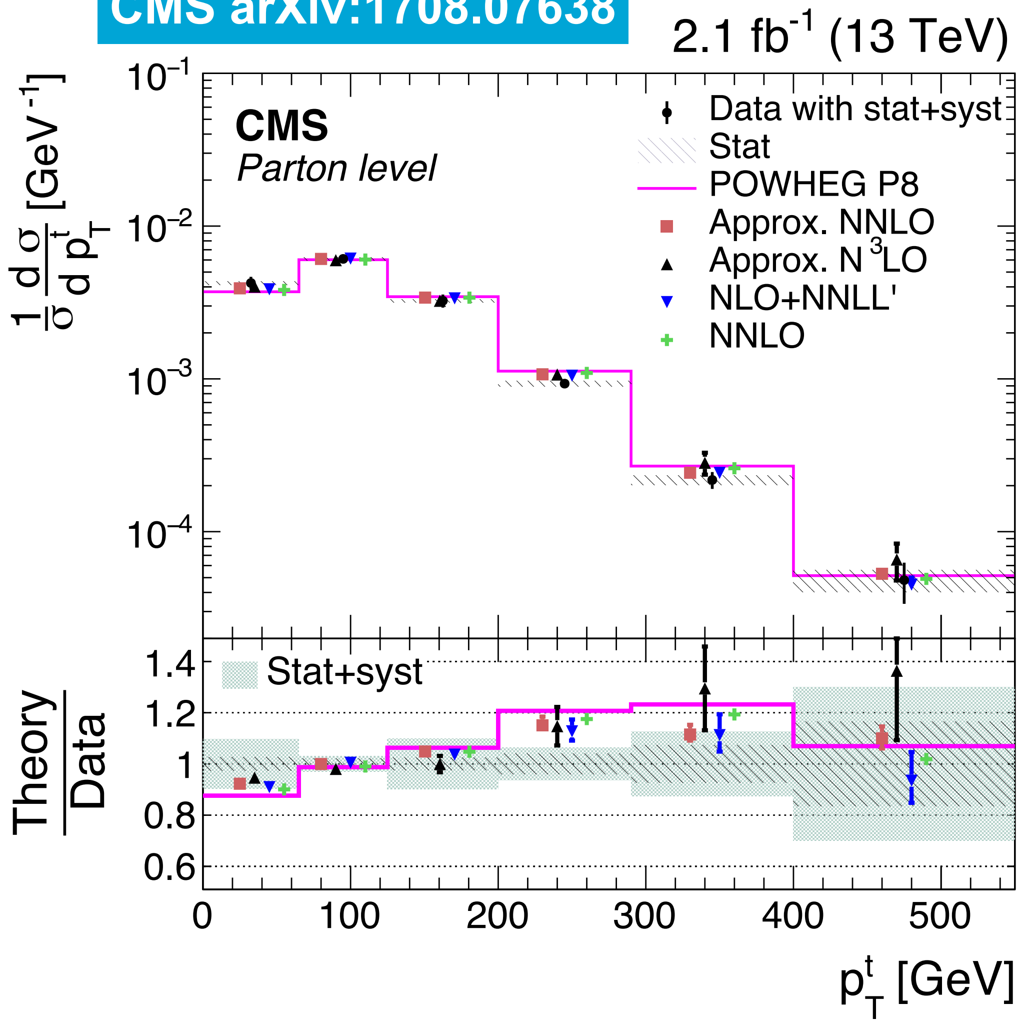
Parton level

Particle level

NNLO Improvements?

✦ Top quark p_T spectrum at parton level vs. NLO+PS and NNLO

CMS arXiv:1708.07638



Top p_T Summary

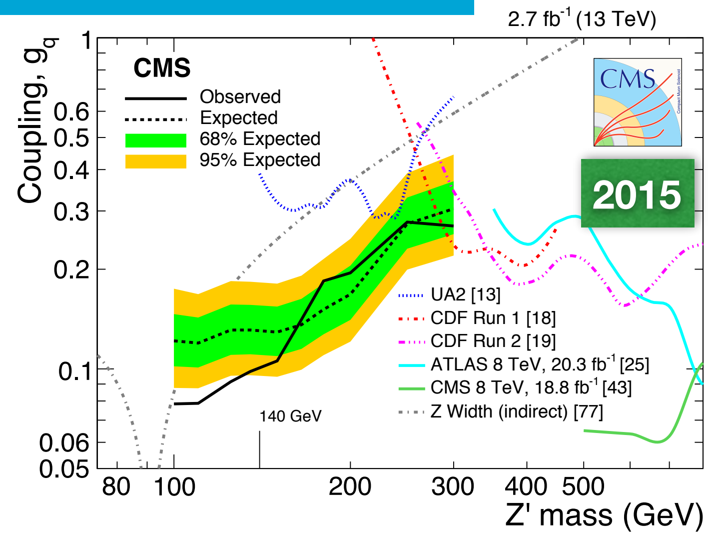
- The jury is still out to as what's going on
- Given the importance of the tt as background for new physics in vast majority of searches, full theoretical understanding of the issue is very important
- Home-grown reweighting method clearly won't suffice for high-precision searches and measurements in Run 3 and beyond
- A long standing problem, really in a desperate need of a proper solution

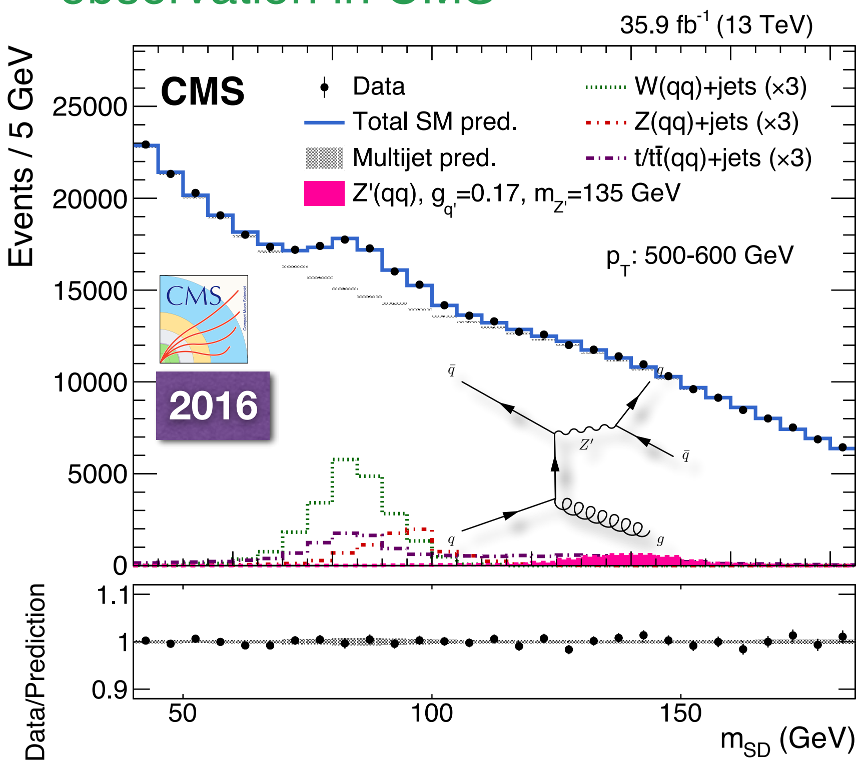
ISR to Rescue

Trijets/jjγ as a Dijet Proxy

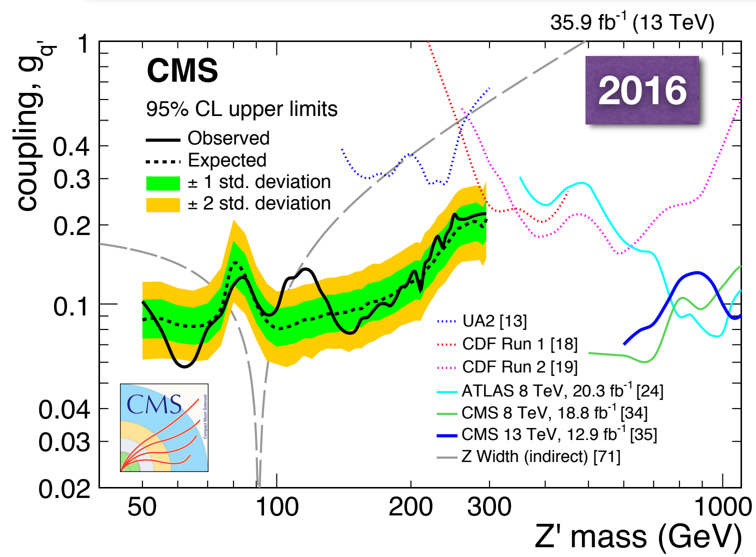
- ✦ A clever way to look for low-mass dijet resonances is to use photon or jet ISR to aid triggering and utilize jet substructure techniques to reconstruct boosted resonance
- ✦ Allows to lower the dijet mass reach to 50 GeV, as demonstrated with the W/Z peak observation in CMS

CMS arXIv:1705.10532



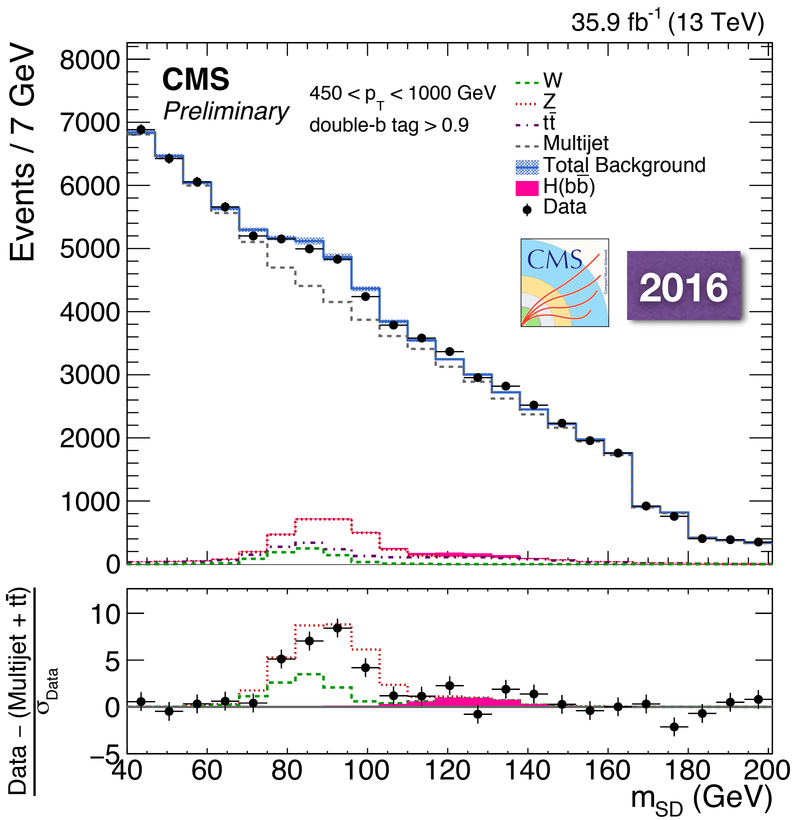


CMS arXiv:1710.00159

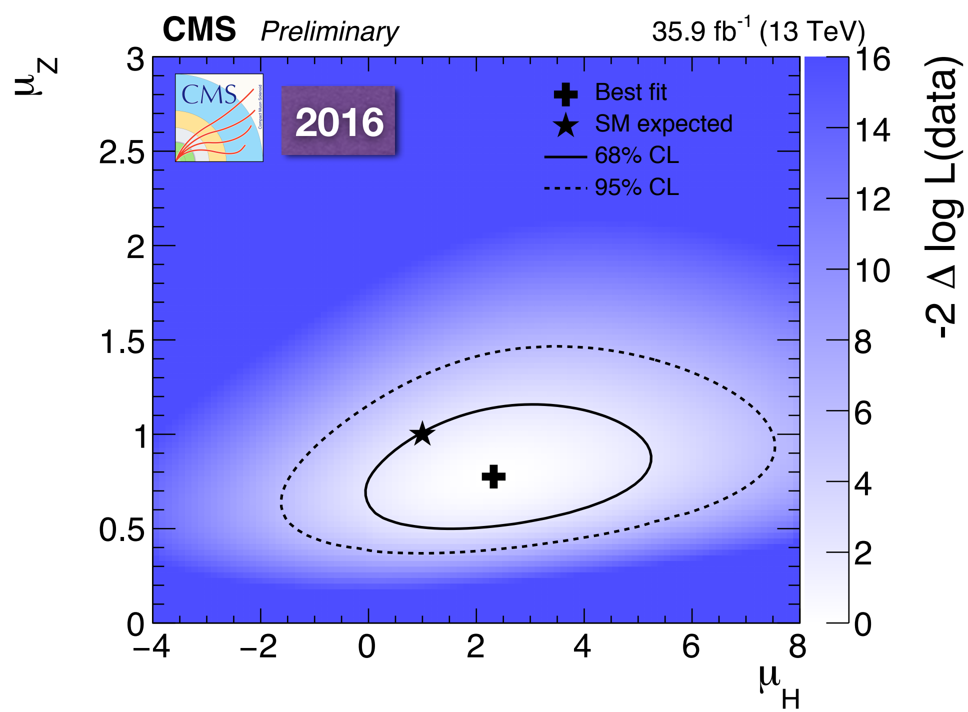


H(bb) in Boosted Channel

- Could use the same approach to look for H(bb) decays in b-tagged large-cone jet
- Currently limited by the trigger; work on specialized triggers is ongoing
- First results are very promising: achieved ~1σ sensitivity w/ 2016 data
- Ultimately would like to probe the H(gg) decay, which can't be seen otherwise at a hadron collider

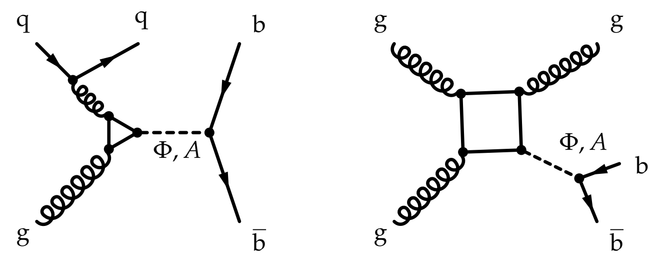


CMS PAS HIG-17-010

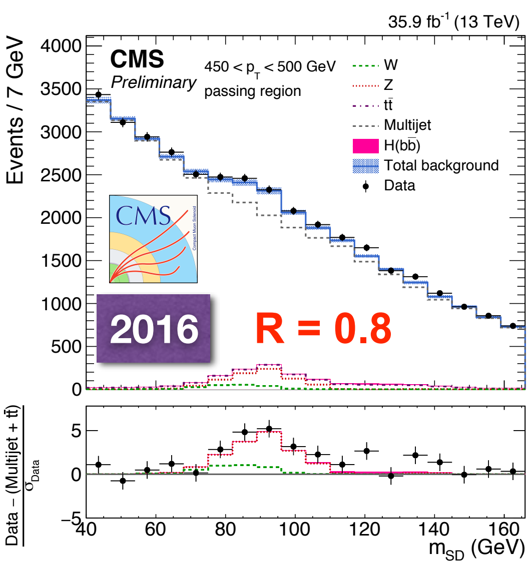


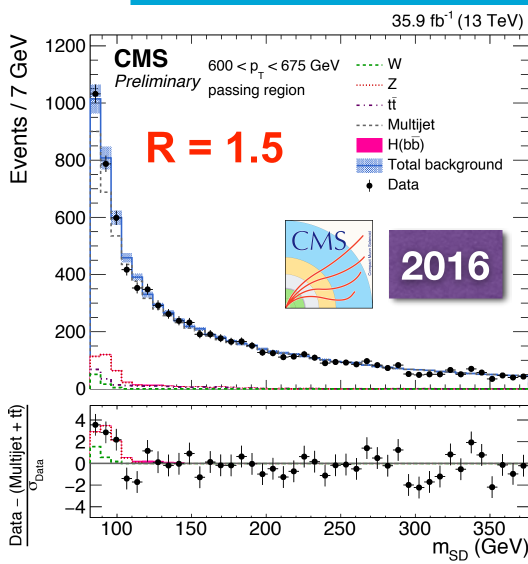
Generalization: φ(bb) Search

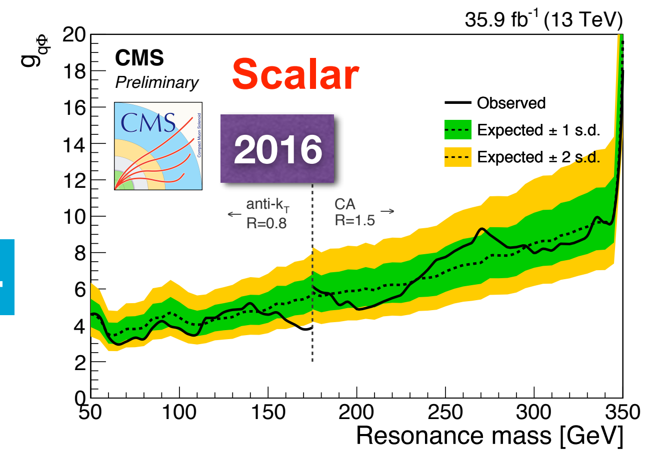
- Generalize the gg → H(bb)+ISR search to an arbitrary (pseudo)scalar resonance produced via gluon fusion
- Use both R=0.8 (AK) and 1.5 (CA) jets to ex mated the mass range to higher masses

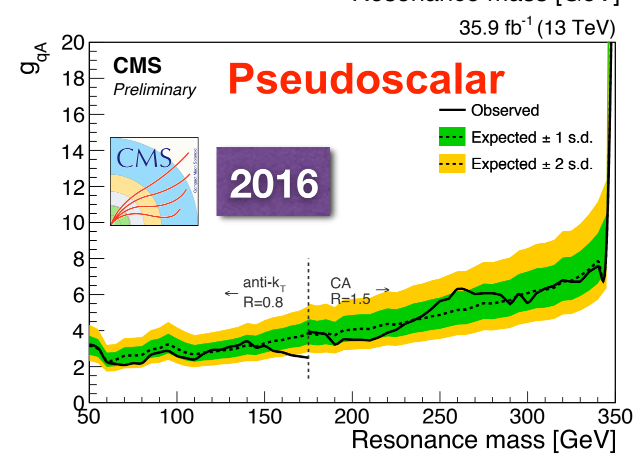


CMS PAS EXO-17-024









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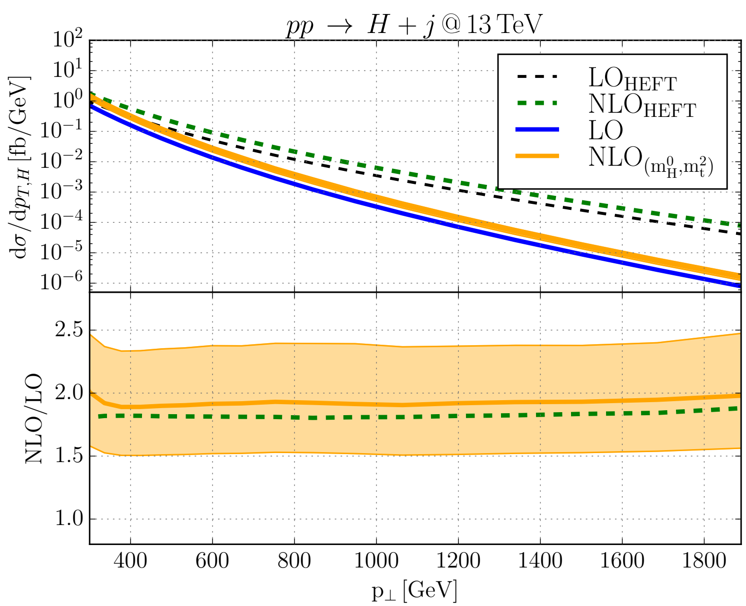
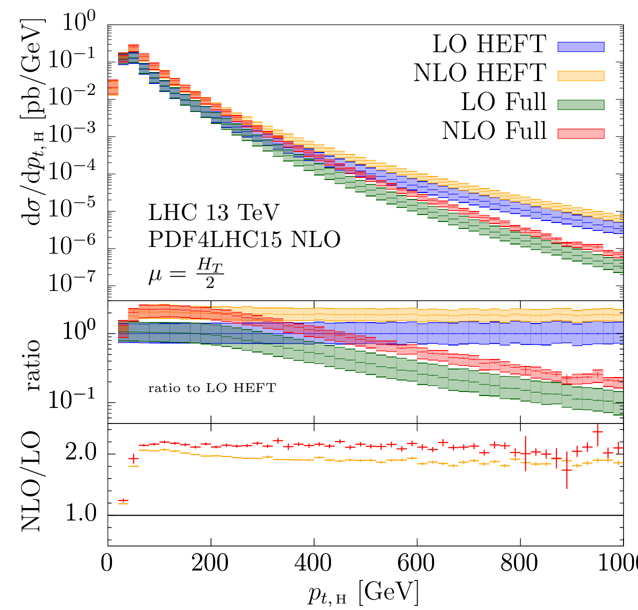
ISR Searches: Theory Issues

- For reliable signal extraction/limits, it's crucial to understand well the p_T spectrum of the (pseudo)scalar resonance produced via gluon fusion at large p_T typical of the ISR searches
- Subject of active theoretical investigation now
- For the Higgs, the state-of-the-art ggF NLO calculations with resolved top quark loop are now available [Kudashkin et al., arXiv:1801.08226; Jones et al., arXiv:1802.00349]
- Ideally would like to combine NNLO EFT and full NLO with resolved loop

arXiv:1801.08226



arXiv:1802.00349



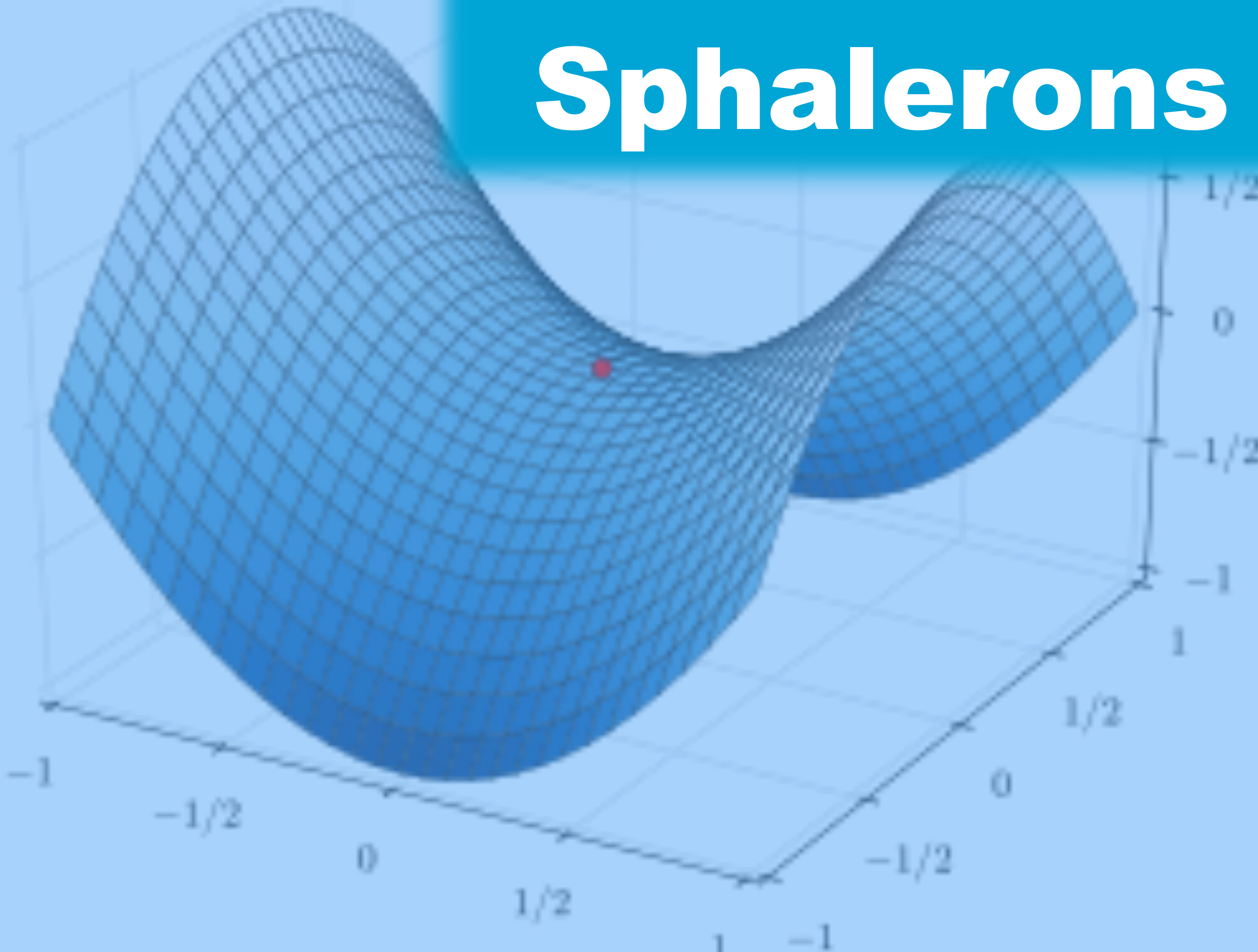
ISR: Theory Issues (cont'd)

- VBF production is a significant (30-50%) contribution at large Higgs boson pT
  - Recently calculated at NNLO fully differentially [Cacciari et al., arXiv:1506.02660; Cruz-Martinez et al., arXiv: 1802.02445] and approximate N^3LO [Dreyer/Karlberg, arXiv: 1606.00840]
  - Cross section for $p_T(H) > 450$ GeV is 4.7 fb
- Open questions:
  - Given the large K-factors, what are the appropriate scale choices?
  - What are reliable uncertainties and how to decrease them?
  - Are EW corrections important?
  - How valid are the Higgs boson corrections for a general (pseudo)scalar in the 100-300 GeV mass range?

Comparison with CMS

- There is a lot of confusion in comparison of the latest results with CMS
  - NLO theory prediction for $p_T(H) > 450$ GeV is $12.9^{+24\%}_{-21\%}$ fb
  - CMS quotes a very different number: 31.7 ± 9.5 fb
- Confusion comes from the two aspects of the measurement:
  - Use of smeared distributions (no unfolding), which increases the cross section by a factor of ~2 due to JES/JEC
  - CMS number corresponds to the leading jet $p_T > 450$ GeV, which is different from $p_T(H) > 450$ GeV because in ~50% of the case the ISR jet is a leading jet, which gives another factor of ~2
- With these caveats, the state-of-the-art theory calculation is quite consistent with what CMS quotes and measures

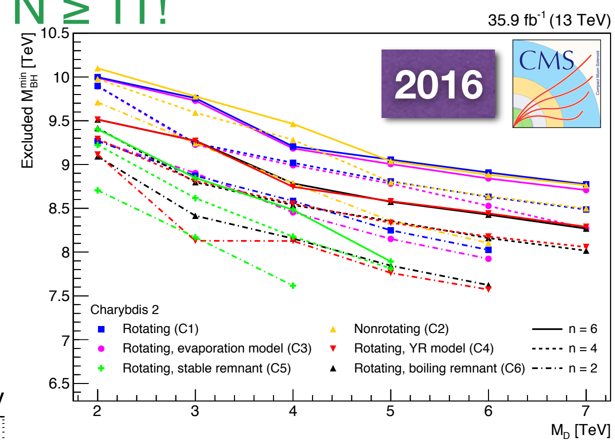
Search for EW Sphalerons

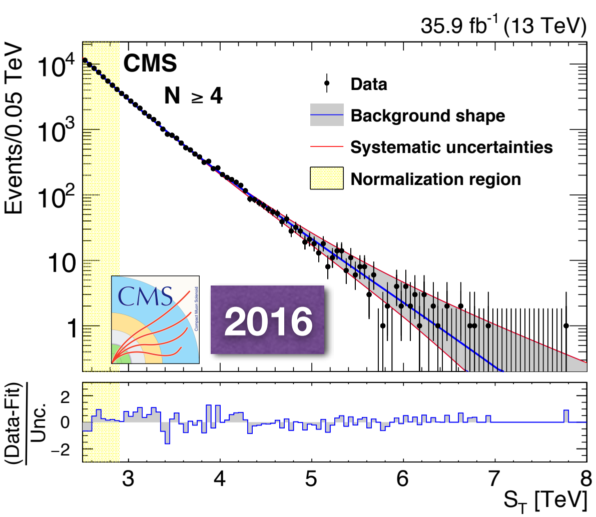


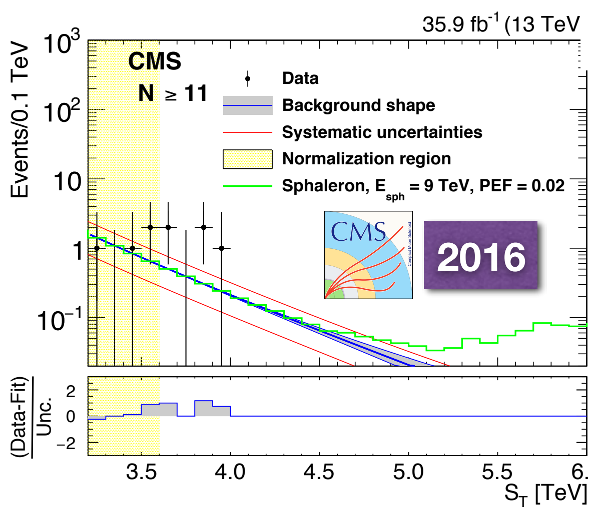
Search for Black Holes

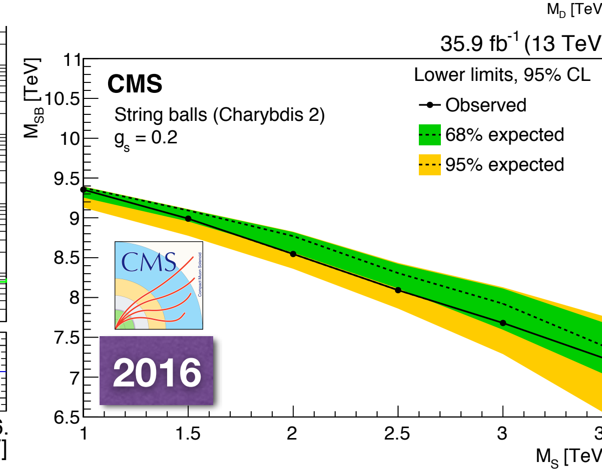
- Traditionally used to probe semiclassical black holes, also provide strong limits on high-multiplicity signatures often expected to come from RPV SUSY decays, axigluons, and other strong dynamics objects, quantum gravity
- Based on the S_T invariance: $S_T = \Sigma p_T^j$ nearly independent of the multiplicity N
- Predict background from N = 3 distribution; go up to N ≥ 11!
- Set both model-independent limits and limits in specific black hole or string ball models
- Limits are as high as 10 TeV on the BH mass

CMS arXiv:1805.06013









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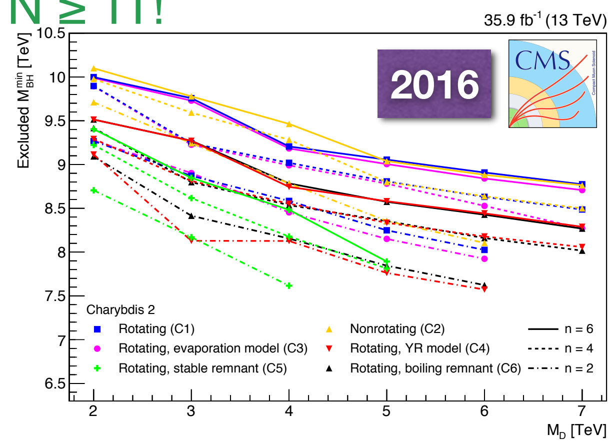
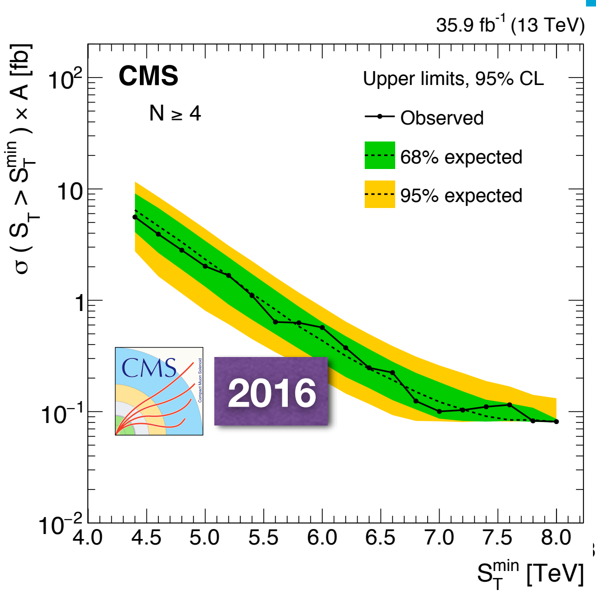
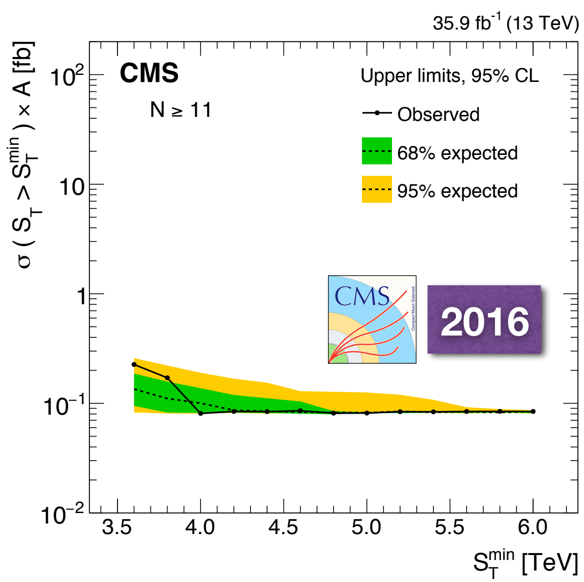
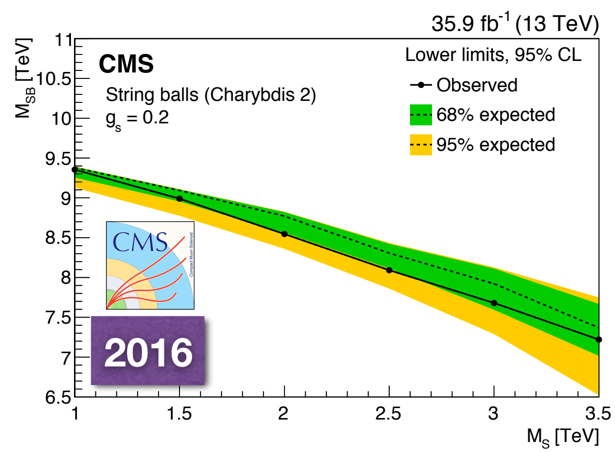






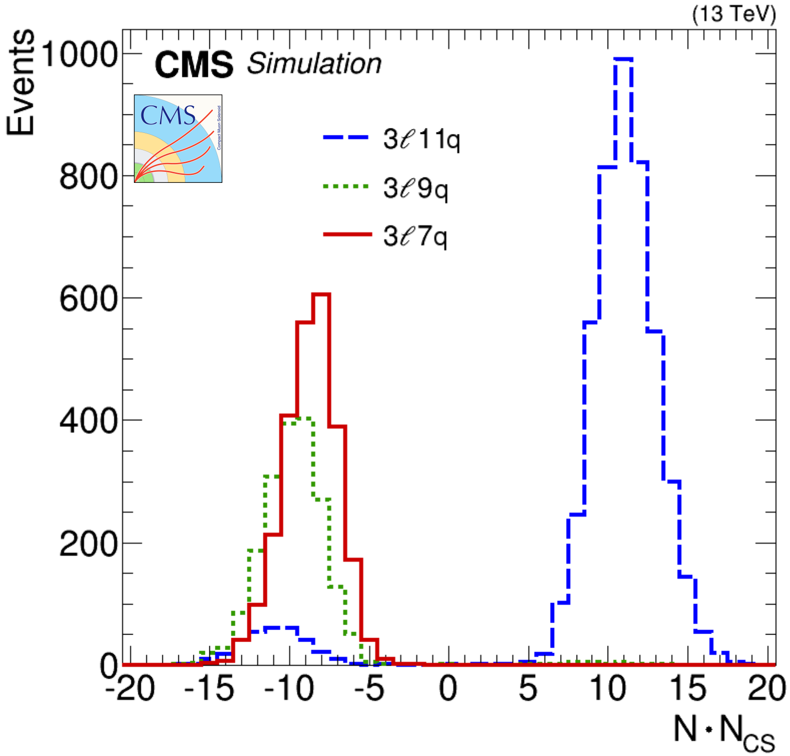


First Search for EW Sphalerons

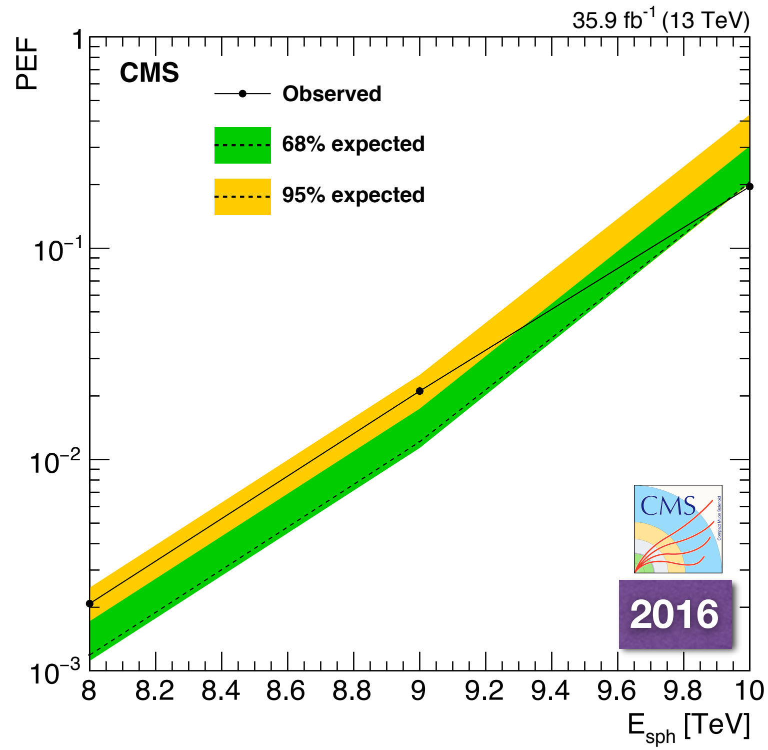
- Can reinterpret this result as a limit on EW sphalerons
- Sphalerons were proposed by `t Hooft as a non-perturbative solution of EW Lagrangian, which results in B and L non-conservation, while conserving B-L
- The discovery of the Higgs boson allowed to calculate the sphaleron transition, which, at LO is at E_{thr} = 9 TeV
- Recent work of Tye/Wong [arXiv:1505.3690] boldly suggested that due to periodicity of the potential there is no exponential suppression for the sphaleron transition just below the threshold, and no suppression at all above the threshold, i.e. observable at the LHC
- Sphaleron transition at leading order results in 12 fermions in the final state (3 x 3 quarks, and 3 leptons, one per generation)
  - Some of the f.s. quarks can "cancel" w/ the initial state, reducing the final-state multiplicity
  - Typical example: $u + u \to u + u + (e^+\mu^+\bar{\nu}_\tau\bar{t}\bar{b}\bar{b}\bar{c}\bar{c}\bar{s}\bar{u}\bar{u}\bar{d}) \to e^+\mu^+\bar{\nu}_\tau\bar{t}\bar{b}\bar{b}\bar{c}\bar{c}\bar{s}\bar{d}$
- Ellis/Sakurai [arXiv:1601.03654] reinterpreted 2015 ATLAS BH search [arXiv: 1512.02586] and set first [phenomenological] limits on EW sphaleron production
- CMS has recently conducted the first dedicated experimental search for EW sphalerons

Limits on EW Sphalerons

- Used BaryoGen generator [arXiv:1805.02786] developed in the course of the analysis
- Limits are set on the pre-exponential factor (PEF), which is the fraction of collisions with the c.o.m. energy above E_{thr}, which undergoes a sphaleron transition
- The limit is PEF < 0.021 @95% CL for the nominal E_{thr} = 9 TeV

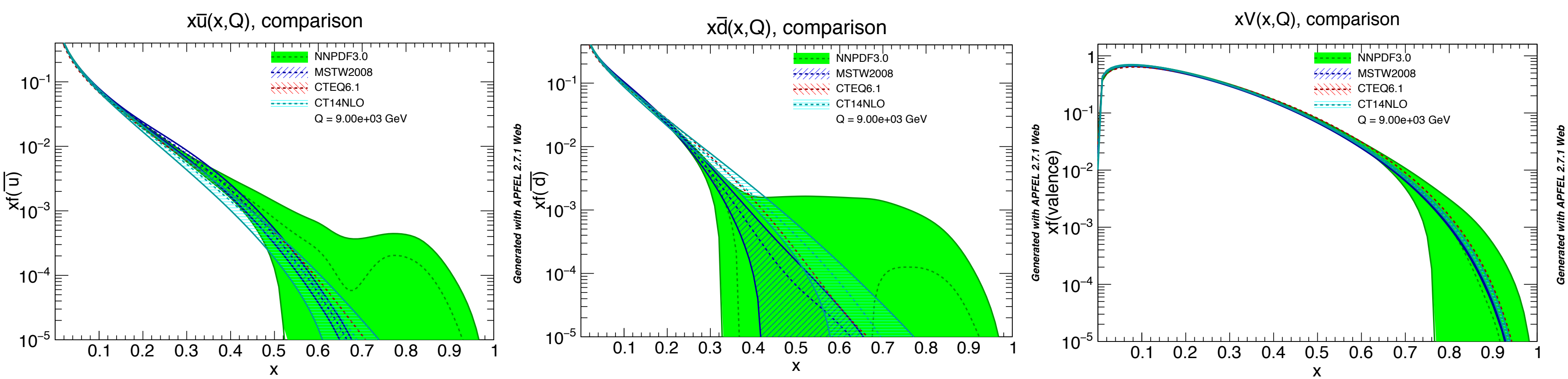


CMS arXiv:1805.06013



The Tricks of PDFs

- In the process of optimizing the sphaleron search, a peculiar feature was noticed in all modern NNPDF sets (2.3, 3.0, 3.1): a fraction of sea quarks at very large Q^2 and x exceeds that of valence quarks
- Not seen in any of the other modern PDFs we looked at (CT14, CTEQ6.1, MSTW, ...)
- While huge uncertainties more or less cover the differences, the central value looks pathological - basically it implies that at large Q2 and x proton mainly consists of sea quarks
- Beware of black boxes in the PDF fits!



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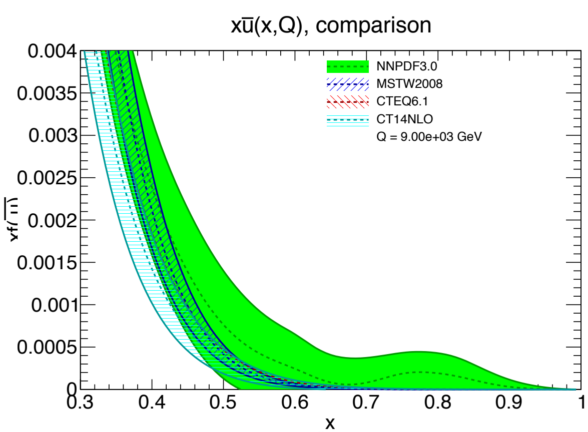
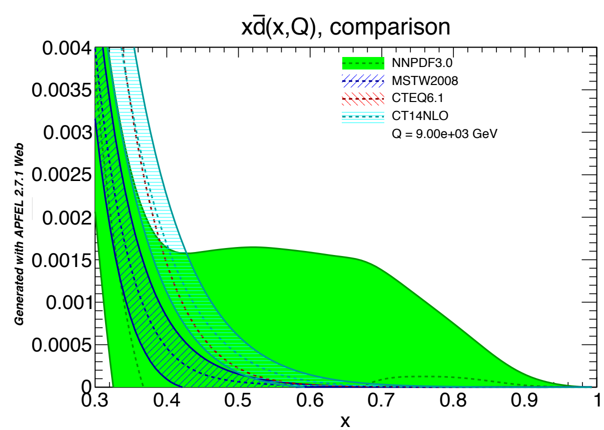
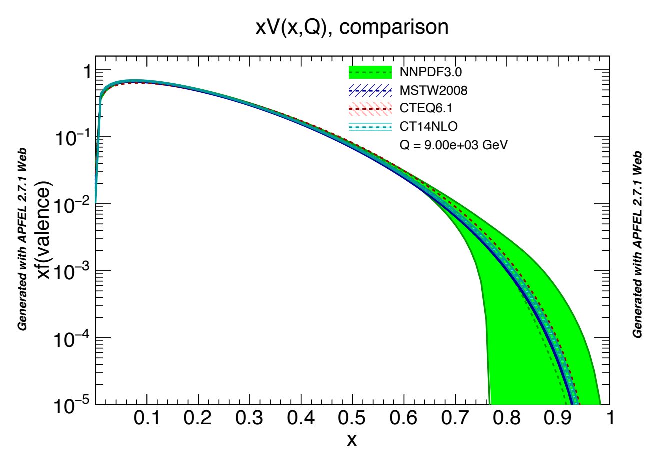
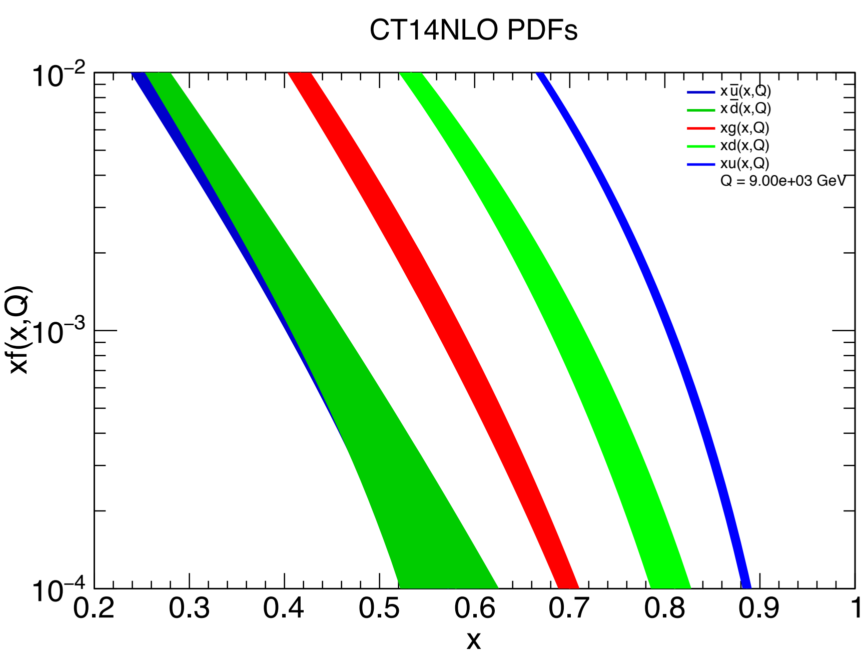


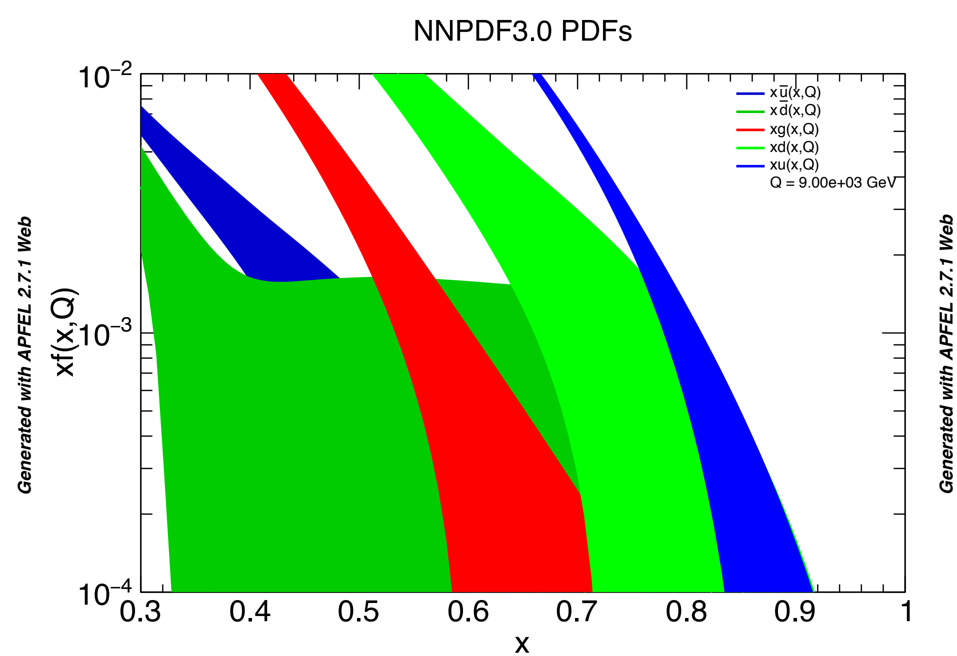




More on PDF Behavior

- At large Q^2 and x NNPDF essentially turns into a random number generator - not very useful for physics predictions
- More LHC data would help, but it would be nice to build in some external physics constraints, which other PDFs seem to have





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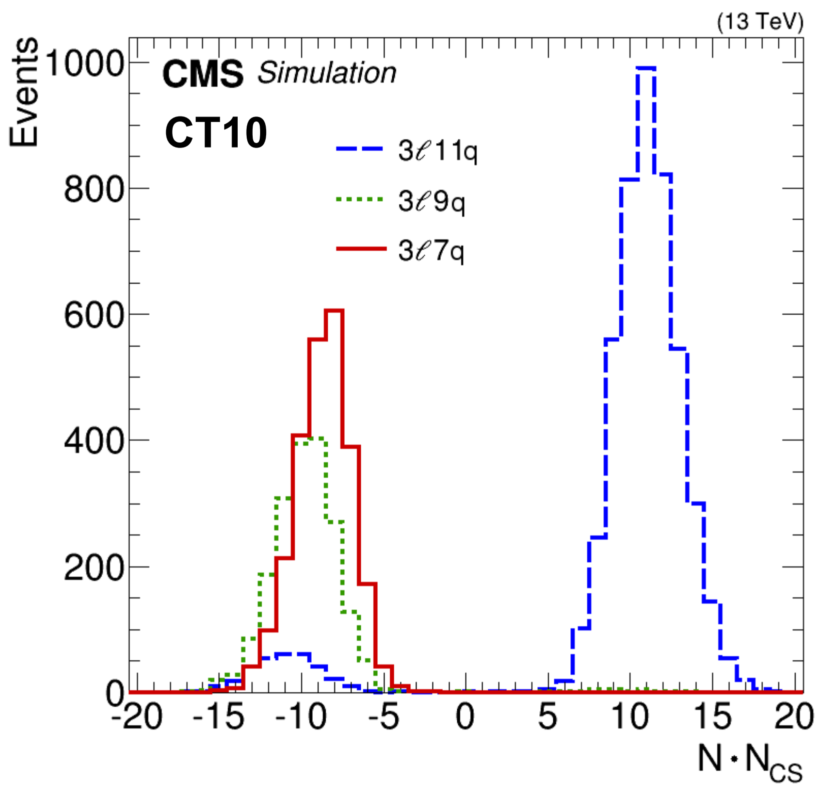
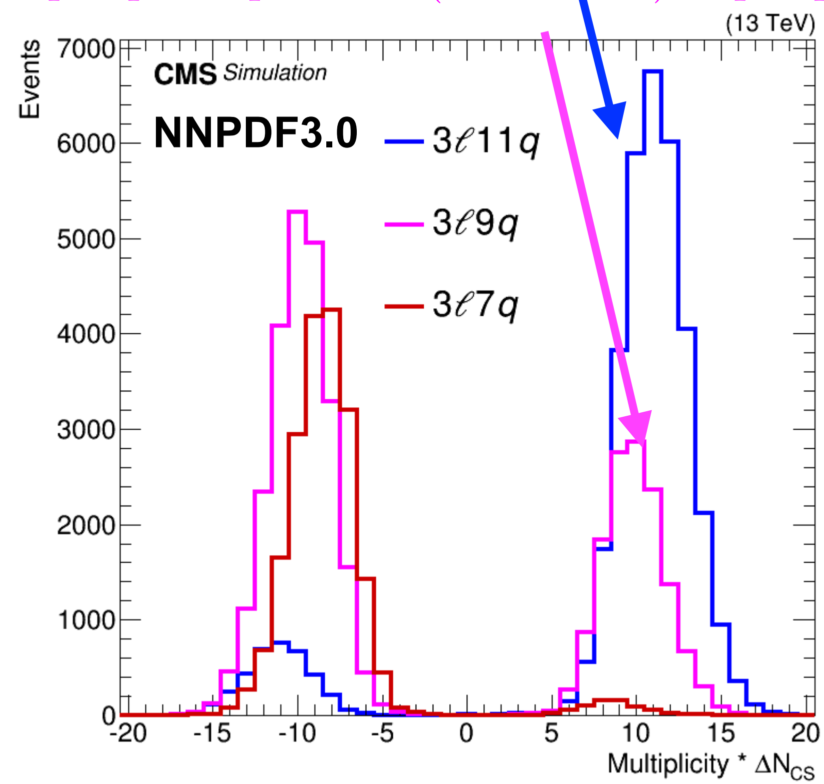
Effect on the Multiplicity

- Transitions involving quarks are badly skewed with NNPDFs, as it gives unphysically high weight to sea antiquarks, resulting in large cancellations for $N_{CS} = 1$



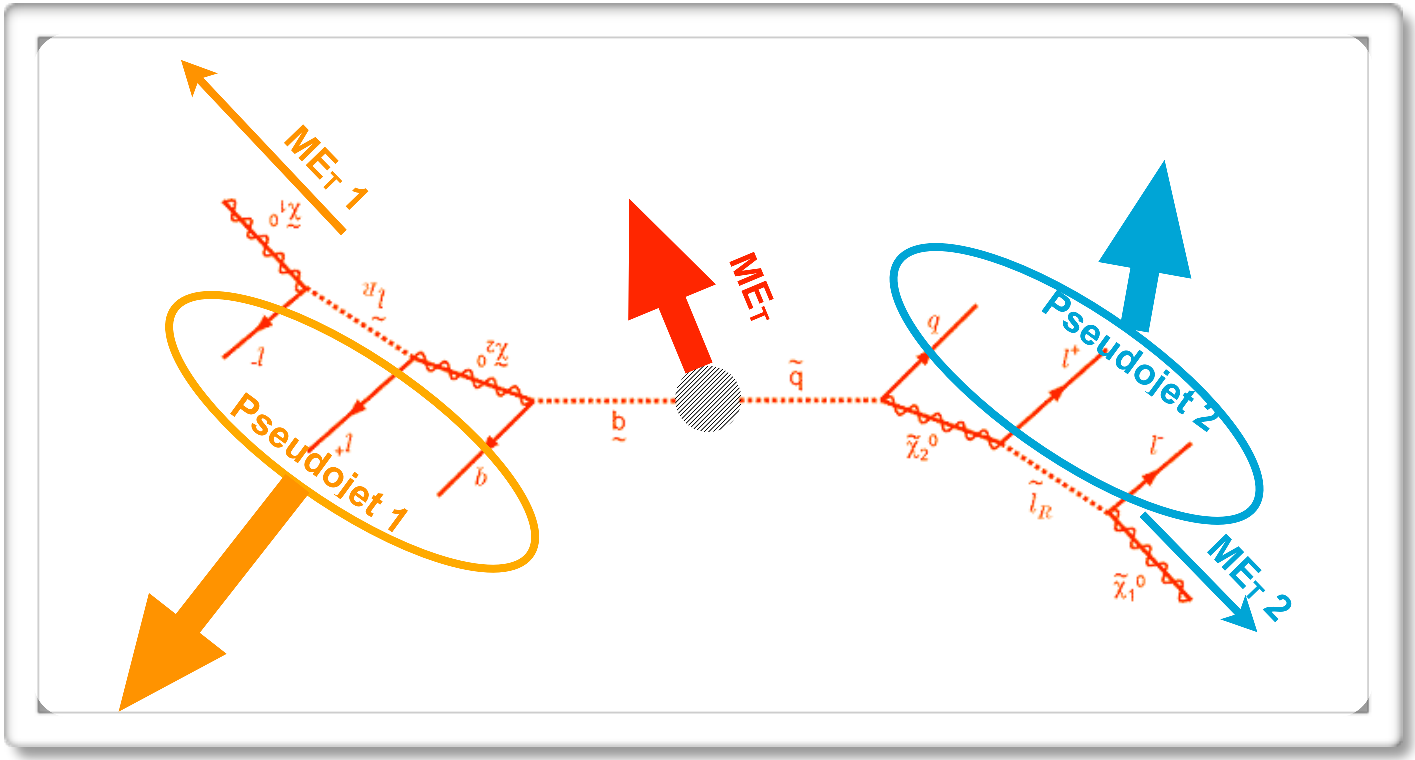
$$q + q' \rightarrow \text{sphaleron}(N_{CS} = +1) + q + q'$$
$$q + \bar{q}' \rightarrow \text{sphaleron}(N_{CS} = +1) + q + \bar{q}'$$



Designer Variables

SUSY Kinematics

- ✦ Look for pair-produced particles that cascade-decade with invisible particle emission
  - ◉ Generally can cluster all visible products in each hemisphere to form "pseudojets", resulting in a dijet + ME_T topology
- ✦ How to optimize the search to reduce backgrounds and at the same time retain information about characteristic SUSY masses?



The α_T Variable

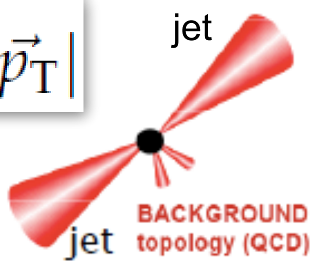
Randall, Tucker-Smith, arXiv:0806.1049

- Alternative approach to requiring large ME_T in the event; does not rely on ME_T reconstruction/tails
- Combine visible decay products in the event into two (pseudo)jets:

$$\alpha_T = E_T^{j_2} / M_T = E_T^{j_2} / \sqrt{H_T^2 - \not{H}_T^2}$$

$$H_T = \sum_{i=1}^{N_{jet}} E_T$$

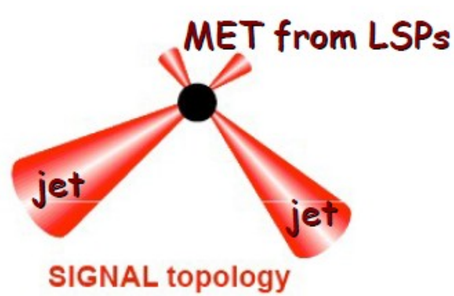
$$\not{H}_T = \left| \sum_{i=1}^{N_{jet}} \vec{p}_T \right|$$

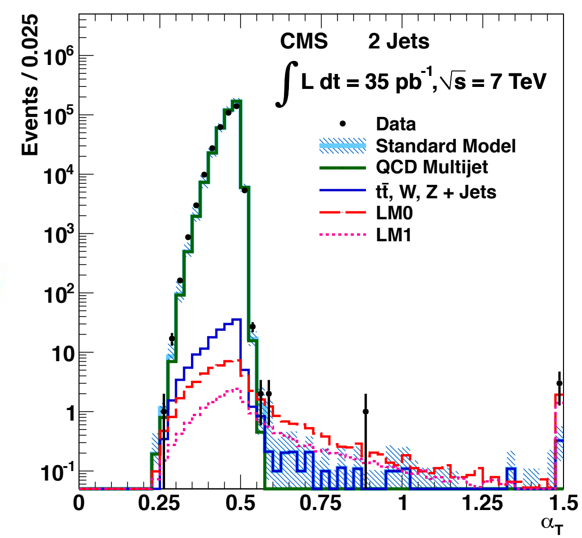


- For a perfectly balanced dijet event, $\alpha_T = 0.5$
- For QCD events with mismeasured ME_T, $\alpha_T < 0.5$
- For signal, long tail of

$$\alpha_T \equiv E_T^{j_2} / M_T(j_1 j_2) = \frac{\sqrt{E_T^{j_2} / E_T^{j_1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$

CMS Collaboration arXiv:1101.1628





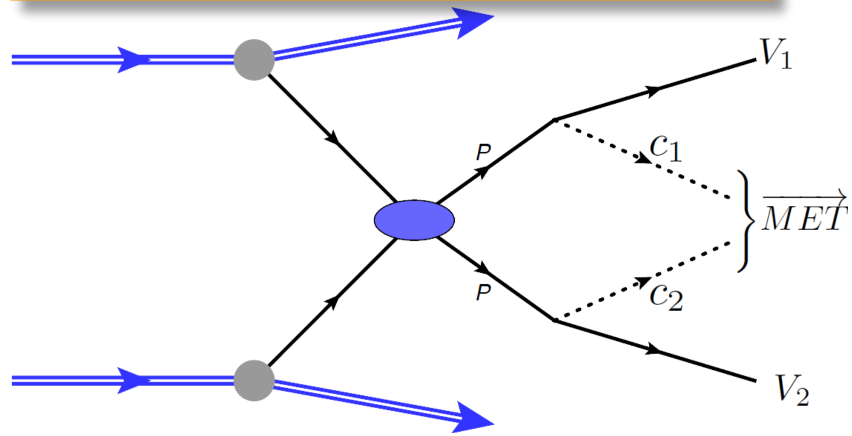
The M_{T2} Variable

- M_{T2}: ***"stransverse mass"*** - a generalization of the transverse mass in case of a pair of invisible particles
- For a simplified case of no extra jets and zero masses for visible and invisible systems:

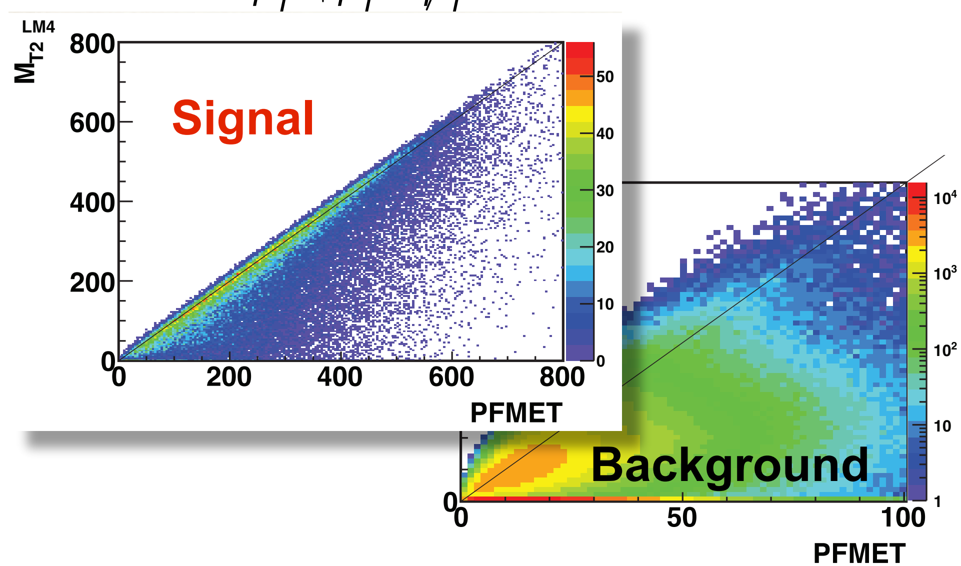
$$(M_{T2})^2 \simeq 2p_T^{vis(1)} p_T^{vis(2)} (1 + cos\phi_{12})$$

  - $M_{T2} \sim ME_T$ for symmetric SUSY-like topologies
- M_{T2} kills QCD background very efficiently:
  - $M_{T2} \sim 0$ for dijets
  - $M_{T2} < ME_T$ in case of mismeasured dijets

Lesters & Summers, hep-ph/9906349

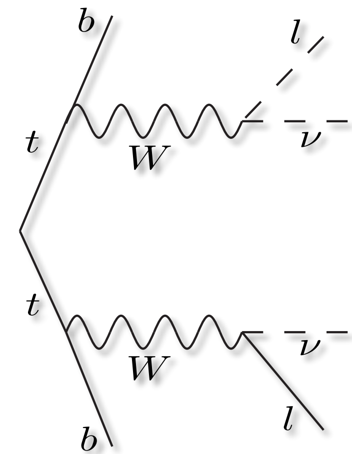


$$M_{T2} = \min_{p_T^{c1} + p_T^{c2} = \not{p}_T} \left[\max \left(m_T^{(1)}, m_T^{(2)} \right) \right]$$

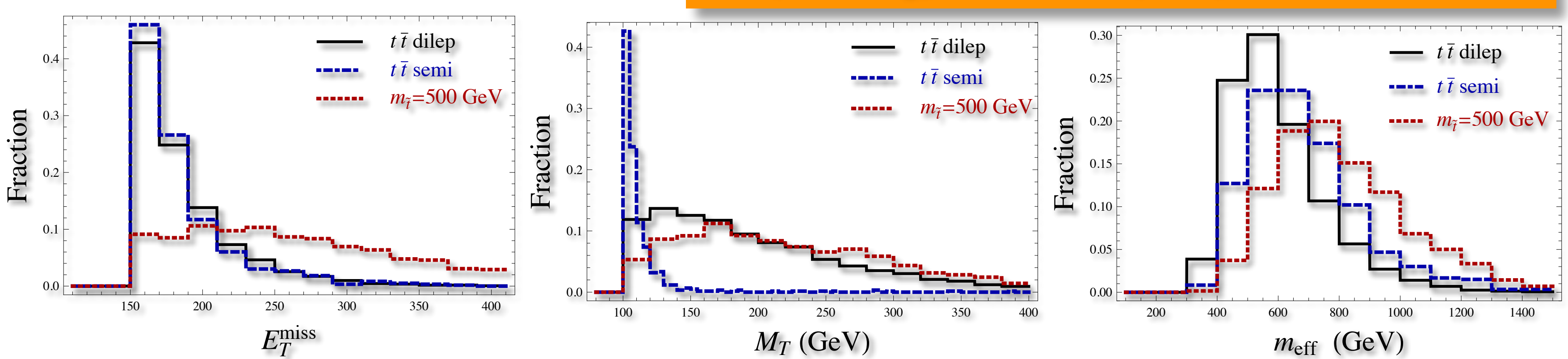


More M_{T2} Variables

- The main variable used in stop searches is a variation of M_{T2} variable, known as M^W_{T2} variable, which is the minimum mother mass compatible with all the decay products and on-shell constraints
- It is designed to specifically kill tt → ll+jets+ME_T background with a lost lepton
- This is a difficult background to deal with as it looks similar to the signal in other distributions, particularly in transverse mass M_T
- The trick of finding the right M_{T2} variable is how to partition the final state particle into visible and invisible states



Bai, Cheng, Gallicchio, Gu, arXiv:1203.4812

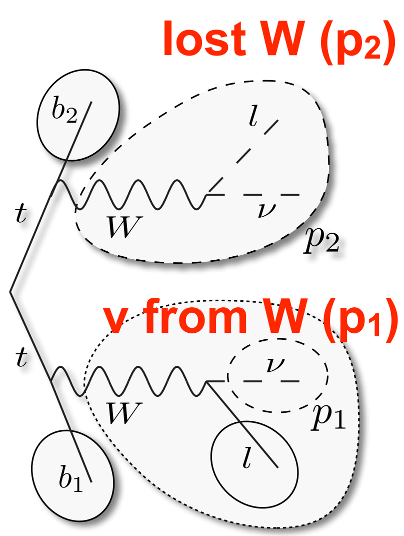


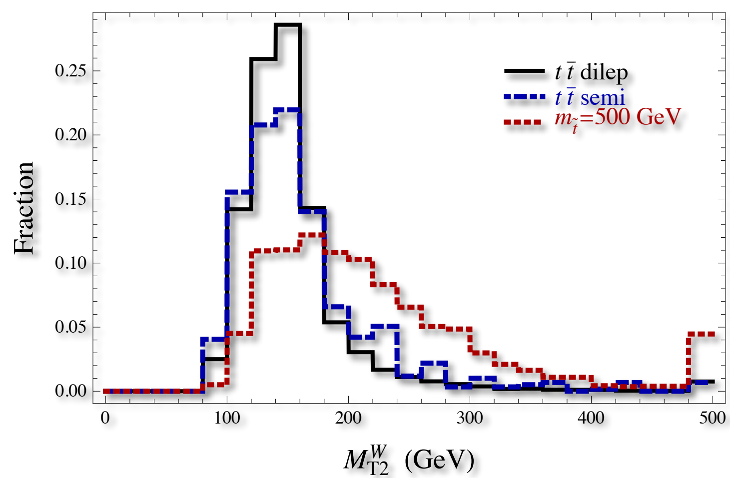
M^W_{T2} Variable

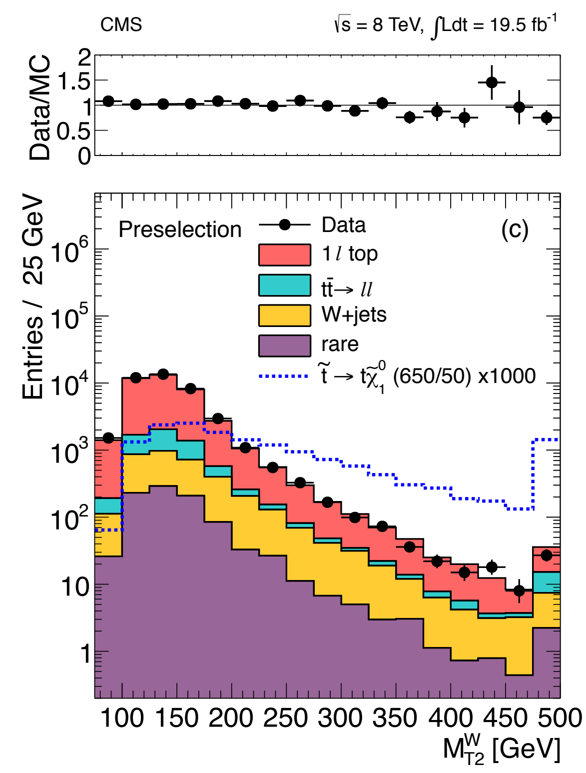
- Here is the definition of the M^W_{T2} variable designed to reconstruct tt events with a lost lepton:

$$M^W_{T2} = \min \left\{ m_y \text{ consistent with: } \left[\begin{array}{c} \vec{p}_1^T + \vec{p}_2^T = \vec{E}_T^{\text{miss}},\ p_1^2 = 0,\ (p_1 + p_\ell)^2 = p_2^2 = M_W^2, \\ (p_1 + p_\ell + p_{b_1})^2 = (p_2 + p_{b_2})^2 = m_y^2 \end{array} \right] \right\}$$

- The tt events with lost lepton exhibit endpoint at $m_y = m_t$, while the signal has long tail







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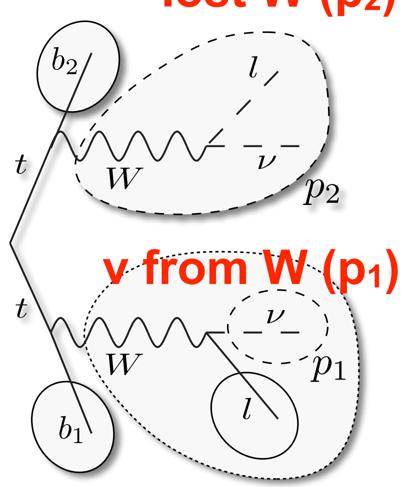
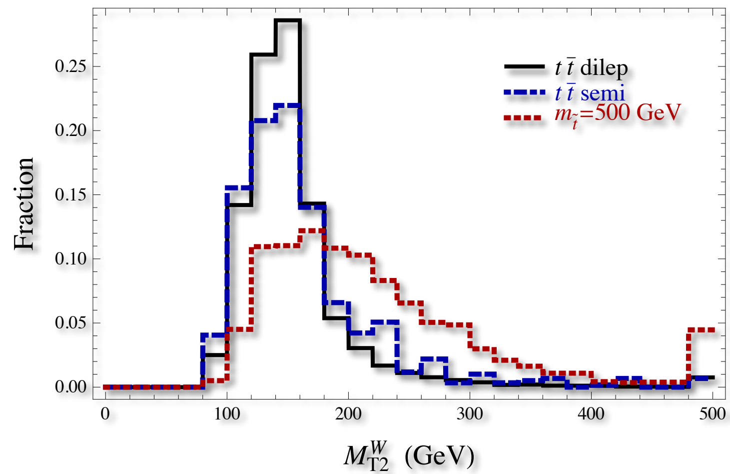
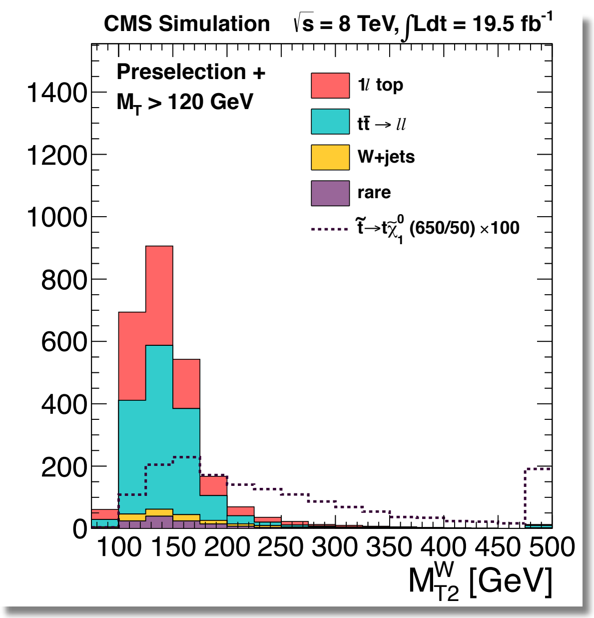


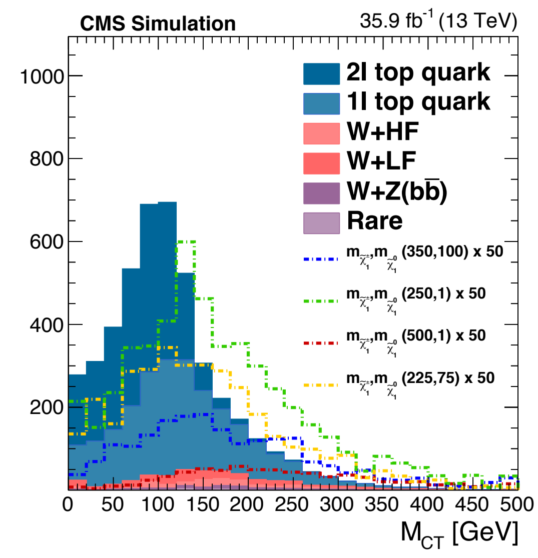




Bai, Cheng, Gallicchio, Gu, arXiv:1203.4812

More M_{T2}-like Variables

- Co-transverse mass M_{CT} [Tovey, arXiv:0802.2879; Polesello, Tovey, arXiv:0910.0174]
  - $M_{CT}^2(v_1, v_2) \equiv [E_T(v_1) + E_T(v_2)]^2 - [\mathbf{p_T}(v_1) - \mathbf{p_T}(v_2)]^2$
    where v_1 and v_2 are visible decay products of the two decay chains
  - Has an endpoint related to the mass of the decaying pair-produced states (X):
    $$\frac{M_X^2 - M_{inv}^2}{M_X}$$
  - For the tt background with lost leptons, using b-jets as visible particles $M_{CT} = \sqrt{2p_T^{b1} p_T^{b2}[1 + \cos(\Delta\phi_{bb})]}$ and taking into account $M_X = M_t$ and M_{inv}, so the endpoint is at the top quark mass

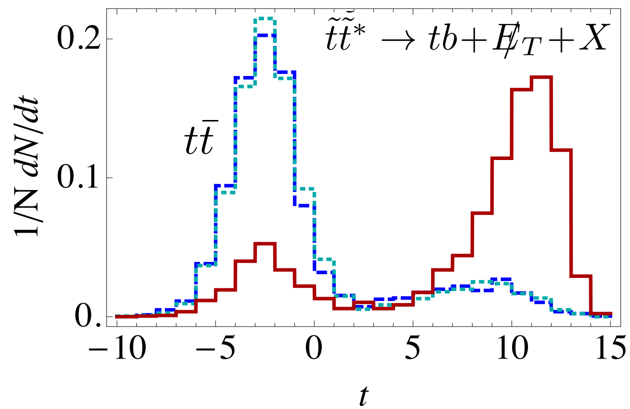


Topness

- Another designer variable to partially reconstruct decays where kinematic information is not sufficient for full reconstruction
  - Example: top quark pair dilepton decay
  - Construct:

$$S(p_{Wx}, p_{Wy}, p_{Wz}, p_{\nu z}) = \frac{(m_W^2 - p_W^2)^2}{a_W^4} + \frac{(m_t^2 - (p_{b_1} + p_\ell + p_\nu)^2)^2}{a_t^4} + \frac{(m_t^2 - (p_{b_2} + p_W)^2)^2}{a_t^4} + \frac{(4m_t^2 - (\sum_i p_i)^2)^2}{a_{CM}^4}, \quad (1)$$

where ai are typical resolutions



  - Define topness [Graesser, Shelton, arXiv:1212.4495]:

$$t = \ln(\min S)$$

  - Minimizes c.o.m. energy of the event within constraints

The Razor Variables

- Introduced as an alternative to M_{T2} and other similar variables
- R-frame: the frame in which momenta of two (pseudo)jets are equal
  - Applicable to a larger class of events than jets+ME_T
- Transforms signal into a peaking distribution on top of exponentially falling background a.k.a. "bump hunt"

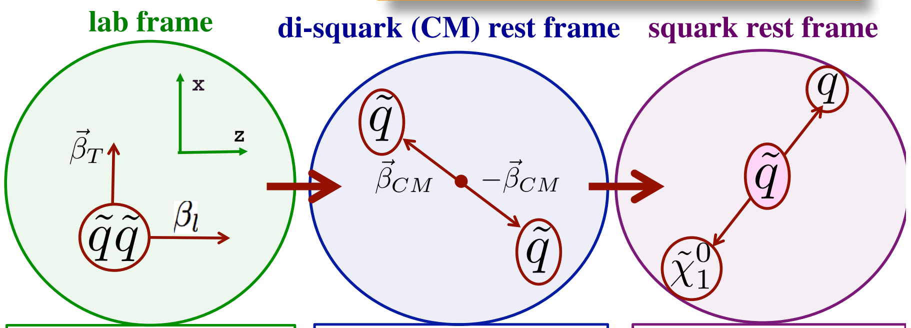
$$M_R = 2\sqrt{\frac{(E^{j1}p_z^{j2} - E^{j2}p_z^{j1})^2}{(p_z^{j1} - p_z^{j2})^2 - (E^{j1} - E^{j2})^2}} \qquad \beta_R = \frac{E^{j1} - E^{j2}}{p_z^{j1} - p_z^{j2}}$$

$$M_T^R = \sqrt{\frac{|\vec{M}|(|\vec{p}_T^{\,j1}| + |\vec{p}_T^{\,j2}|) - \vec{M}\cdot(\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$

$$R \equiv \frac{M_T^R}{M_R}$$

R ~ ½ for signal and is exponentially falling for QCD background

Rogan, arXiv:1006.2727



$|\vec{\beta}_T| \ll 1$

The di-squark rest frame is approximately related to the lab frame by one longitudinal boost

$\vec{\beta}_T = 0$

$2\gamma_{CM} M_{\tilde{q}} = \sqrt{\hat{s}}$

Squarks are heavy, so they are preferentially produced near threshold ($\gamma_{CM} \approx 1$)

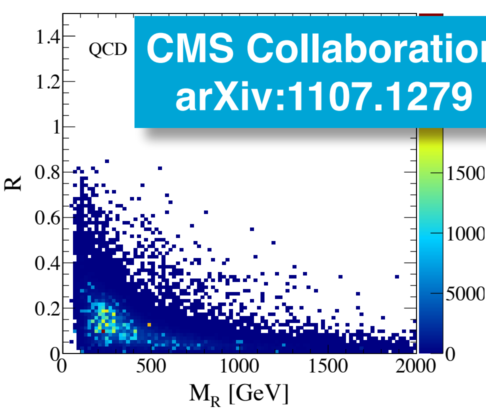
$\vec{\beta}_{CM} \to 0$

$M_\Delta = \frac{M_{\tilde{q}}^2 - M_{\chi}^2}{M_{\tilde{q}}}$

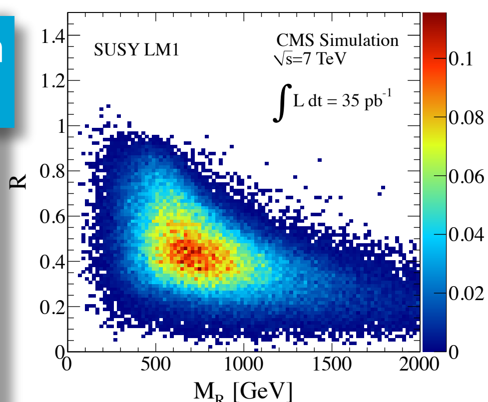
Characteristic scale of process is reflected in momenta of quarks and LSP's

$M_R \to M_\Delta$ for $\gamma_{CM} \to 0$: peaks for signal!

M_T^R has an endpoint at M_Δ

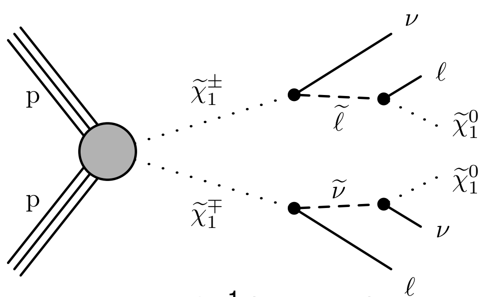


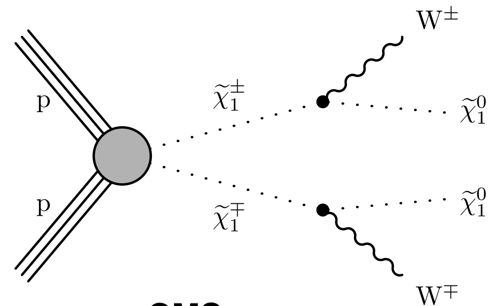
CMS Collaboration arXiv:1107.1279

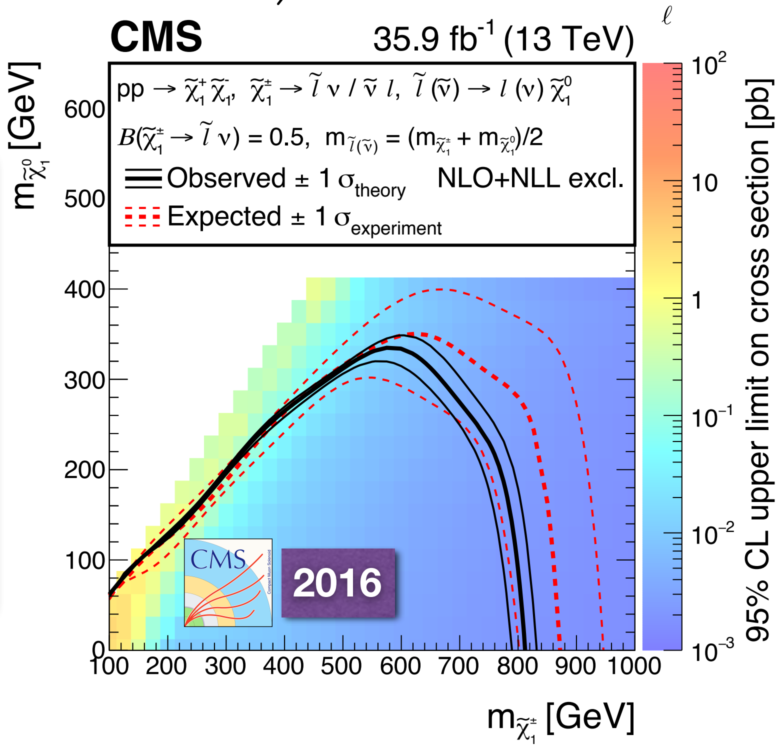


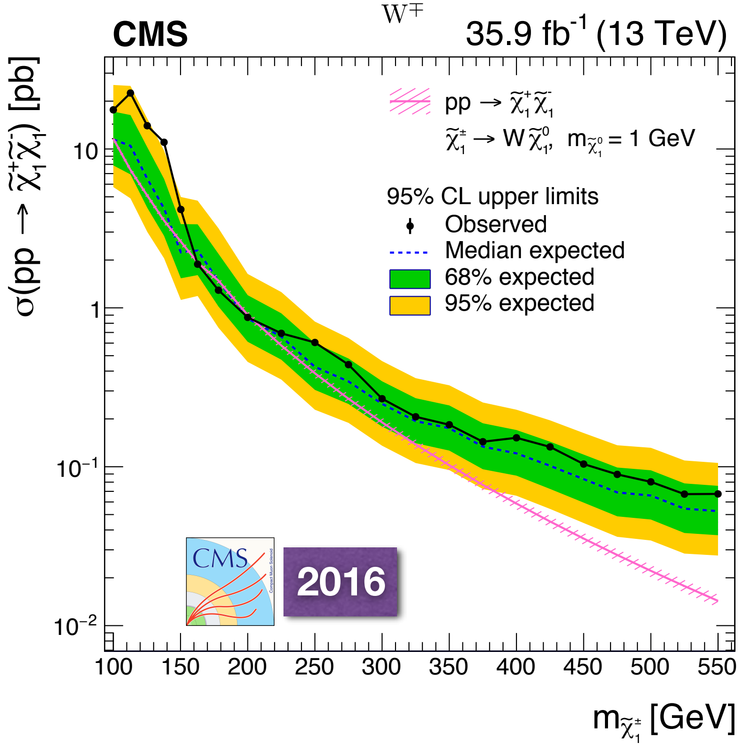
Example of Designer Variable Use

- Search for EW SUSY production in the dilepton channel, using M_{T2} to suppress dominant tt and WW background









CMS arXiv:1807.07799

Example of Designer Variable Use

BROWN

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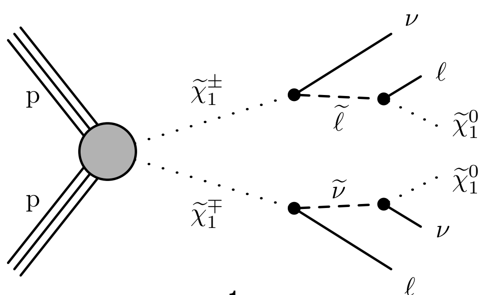

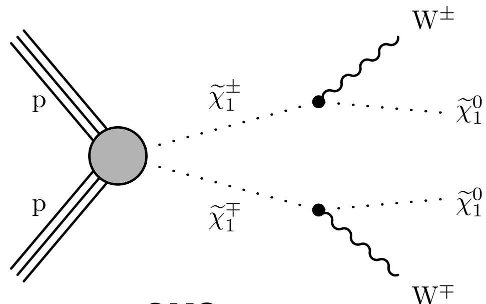

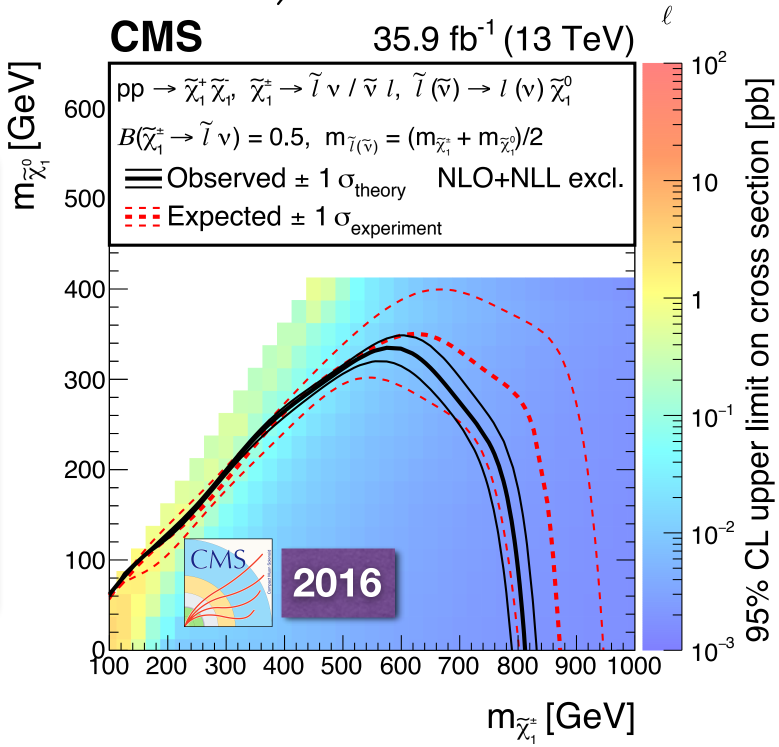

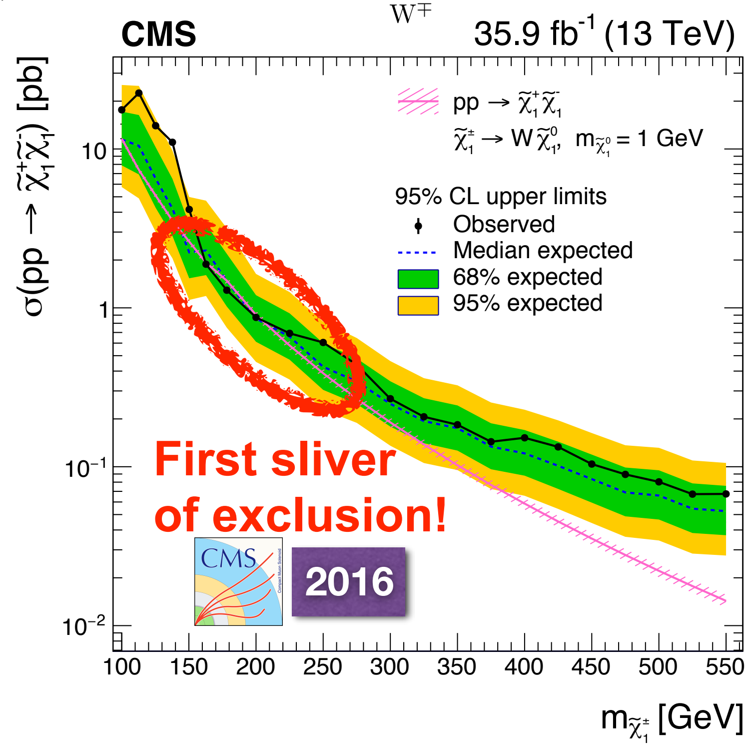

CMS arXiv:1807.07799

Greg Landsberg - CMS Searches meet Theory - AMPHEP2018

Designer Variables: Summary

- These variables have been a significant help in many SUSY and non-SUSY searches
- Might help other channels, such as H(WW)H(bb)
- While multivariate analysis techniques could in principle compete with the use of these variables, having physics captured in a dedicated variable makes the analysis more straightforward and also helps resolving complicated correlations
  - Could be used with the matrix element weighting techniques
- Would like to see theoretical work in this direction continuing

Conclusions

- High-precision era of LHC physics is upon us
- It's more and more likely that if new physics is to be found at the LHC, it's not going to be via a smoking gun signature, but rather via a subtle deviation from the SM predictions
- Precision theoretical understanding of various backgrounds to these searches is therefore going to be more and more important
- I've gave a few examples where the recent progress in theory resulted in a significant improvement of experimental sensitivity
- I also pointed out a few places where further progress on the theory side is very important for the experiment
- With the theory and experiment cross-pollinating each other, we are moving into the domain of precision searches, which hopefully will soon result in a discovery!