IN CLOSING

Felix Yu
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EFTs for Collider Physics, Flavor Phenomena and EWSB
November 13, 2014

In Closing
Our Story Thus Far

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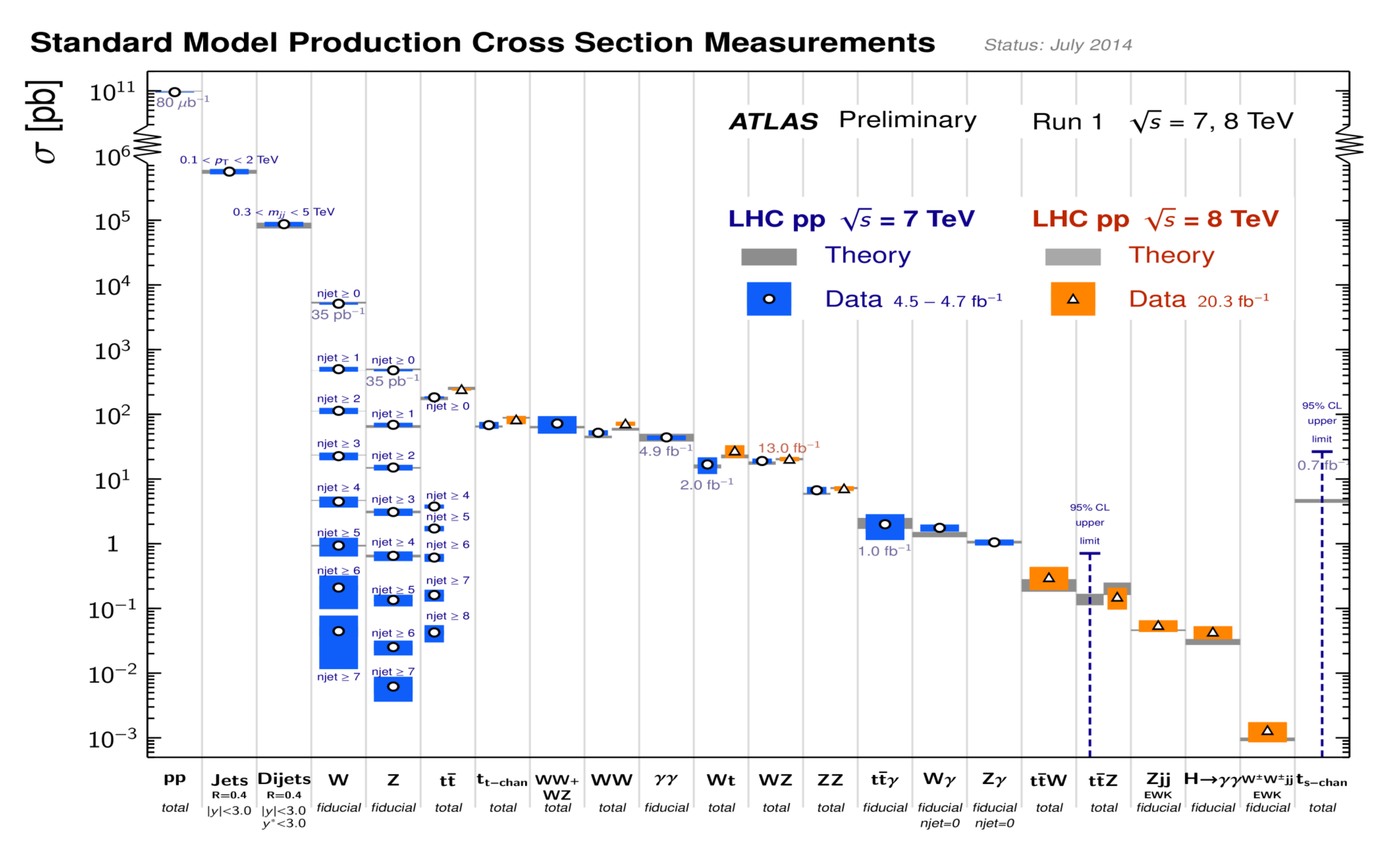
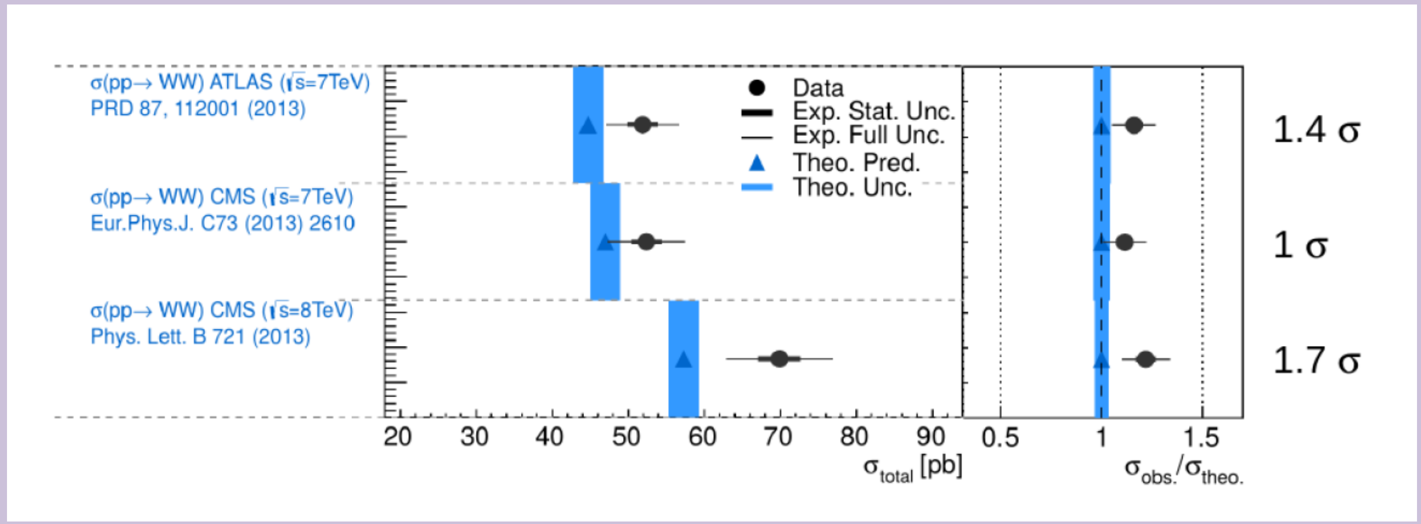
The SM works

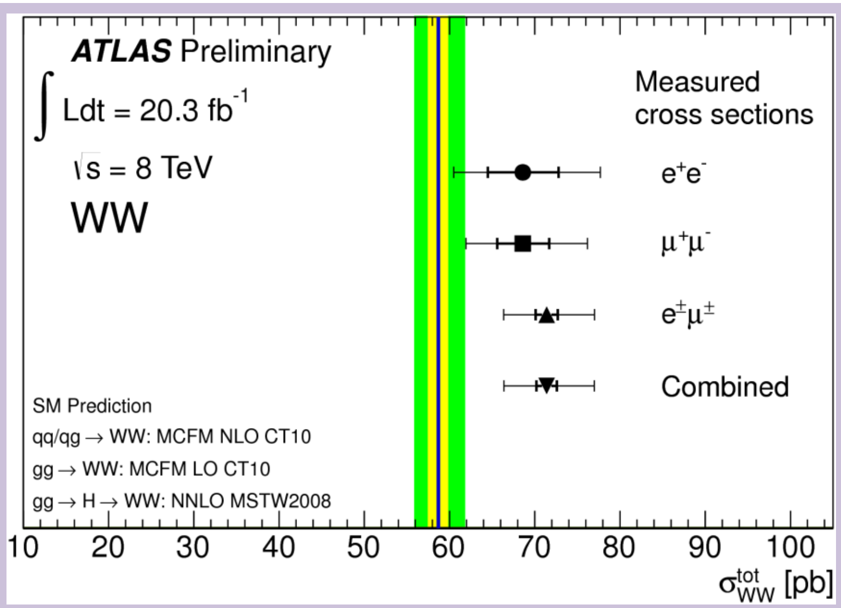


ATLAS https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

Also CMS https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

The SM works (?)

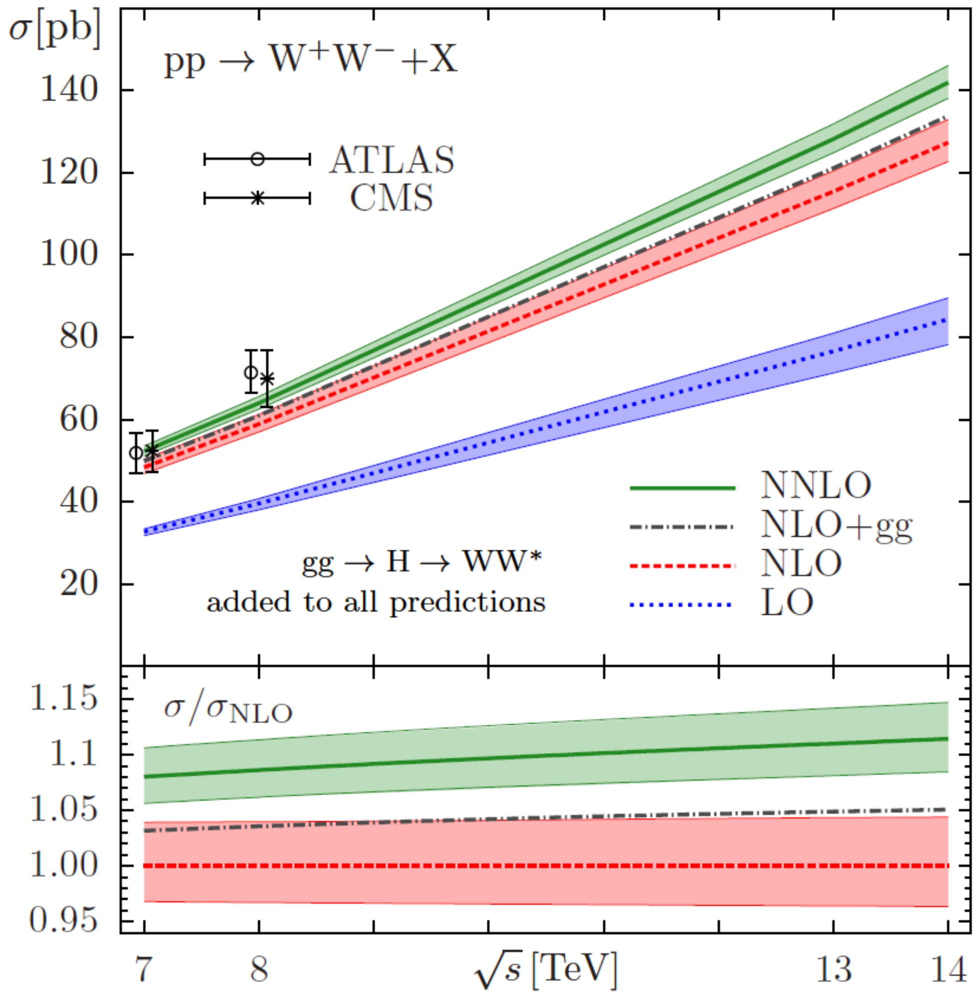




von Manteuffel

The SM works (!)

Result: W^+W^- production at NNLO



von Manteuffel

Gehrmann, Grazzini, Kallweit, Maierhöfer, AvM, Pozzorini, Rathlev, Tancredi '14

Aside 1

Anonymized comment overheard during this workshop

"Disgusting level of agreement"

Collective mood since the Higgs discovery

Disgusting (yet impressive) level of agreement

Collective mood since the Higgs discovery

Disgusting (yet impressive) level of agreement

Can the SM be right?

Aside 2

2nd Anonymized comment overheard during this workshop

"But we know it's wrong"

The SM lives on, but only as an EFT

- Quadratic sensitivity of Higgs mass to new scales
- Fermion masses and mixings
- Dark matter
- Neutrinos
- Baryogenesis
- Inflation
- …

Disgusting (yet impressive) level of agreement between SM and data,
but a spectacular failure in many regards

Attacking the SM

- Flavor
- Electroweak precision
- Collider

Attacking the SM

- Flavor
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Ultimately, precision calculations, discrepant data, and robust interpretations will spell the downfall of the SM, no matter which sector breaks through first

The Flavor Attack

Three Basic Requirements

1. **Precise CKM parameters from tree level decays (negligible NP contributions)**

Main Targets : $|V_{ub}|,\ |V_{cb}|,\ \gamma$

2. **Precise Lattice QCD Calculations**

Main Targets : $F_{B_s}, F_{B_d}, \hat{B}_{B_d}, \hat{B}_{B_s}, B_8^{(2/3)}, B_6^{(1/2)}$ + formfactors $(B \to K^*, K)$

Significant progress in the last years (dynamical fermions) but higher precision needed in order to see small NP effects.

Buras

3. **NLO + NNLO QCD Corrections and NLO Electroweak Corrections to Wilson Coefficients**

1988 - 2014 Task completed !! 26 Years !

AJB: 1102.5650 (Update, Sept. 2014)

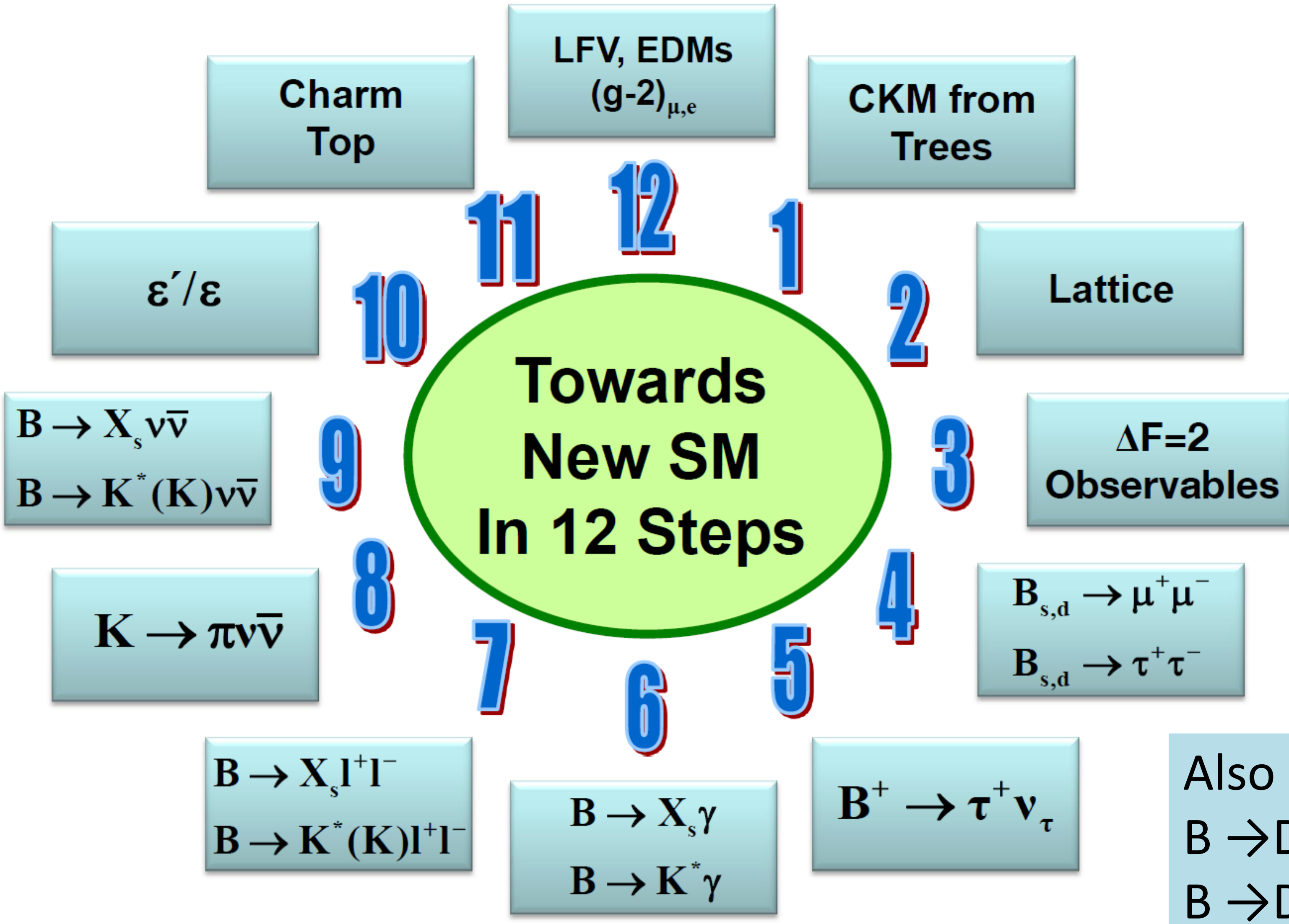
Most recent

NLO Electroweak to $B_{s,d} \to \mu^+\mu^-$ — Bobeth, Gorbahn, Stamou

NNLO QCD to $B_{s,d} \to \mu^+\mu^-$ — Hermann, Misiak, Steinhauser

The Flavor Attack – a 12 step program

Buras



Also
$B \to D \tau \nu$
$B \to D^* \tau \nu$

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SM starting to crack?

Tensions in $b \to s$ transitions, November 2014

Straub

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	[16, 19.25]	0.47 ± 0.05	0.31 ± 0.07	CDF	+1.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	A_{FB}	[2, 4.3]	-0.04 ± 0.03	-0.20 ± 0.08	LHCb	+1.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	[2, 4.3]	0.79 ± 0.03	0.26 ± 0.19	ATLAS	+2.7
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	[2, 4.3]	-0.16 ± 0.03	0.12 ± 0.14	LHCb	−2.0
$\bar{B}^- \to \bar{K}^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	[4, 6]	0.50 ± 0.08	0.26 ± 0.10	LHCb	+1.9
$\bar{B}^- \to \bar{K}^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	[15, 19]	0.59 ± 0.06	0.40 ± 0.08	LHCb	+1.8
$\bar{B}^0 \to \bar{K}^{0}\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	[0.1, 2]	2.71 ± 0.53	1.26 ± 0.56	LHCb	+1.9
$\bar{B}^0 \to \bar{K}^{0}\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	[16, 23]	0.93 ± 0.10	0.37 ± 0.22	CDF	+2.3
$B_s \to \phi\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	[1, 6]	0.39 ± 0.06	0.23 ± 0.05	LHCb	+2.0

$\Rightarrow$ QCD or New Physics or . . . ?

[Altmannshofer, DS]

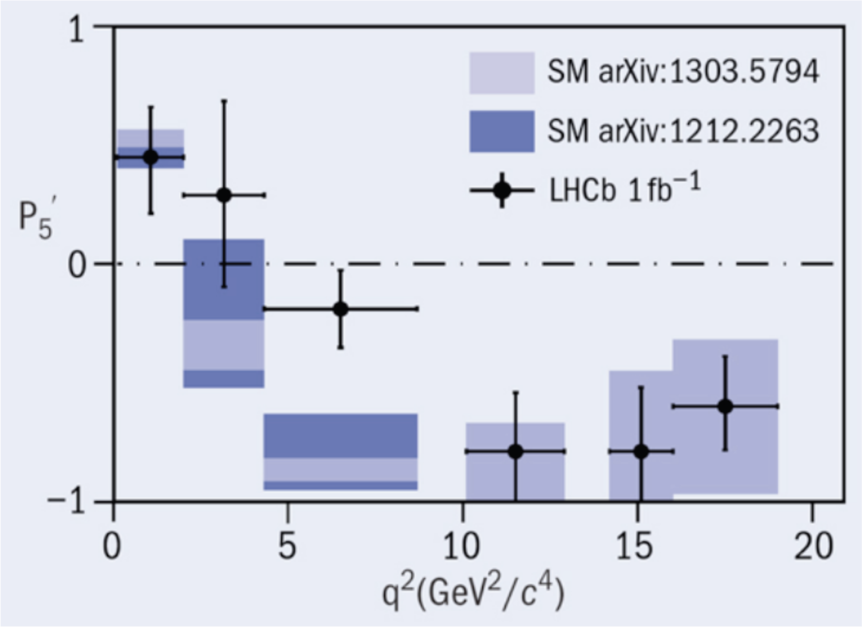
SM starting to crack?

P_5' "anomaly"

S. Jäger

$$\langle P_5' \rangle = \frac{\langle \beta(\mathrm{Re}[(H_V^- - H_V^+)H_A^{0*} + (H_A^- - H_A^+)H_V^{0*})\rangle}{\sqrt{\langle \beta^2 |H_V^0|^2 + |H_A^0|^2)\rangle \langle \beta^2(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2)\rangle}}$$

CERN Courier, December 2013



Descotes-Genon, Matias, Virto [DMV]

SJ, J Martin Camalich (4.3..8.68 bin is actually a private update, not stated in paper)

* Significance of the effect depends strongly on treatment of theory uncertainties!

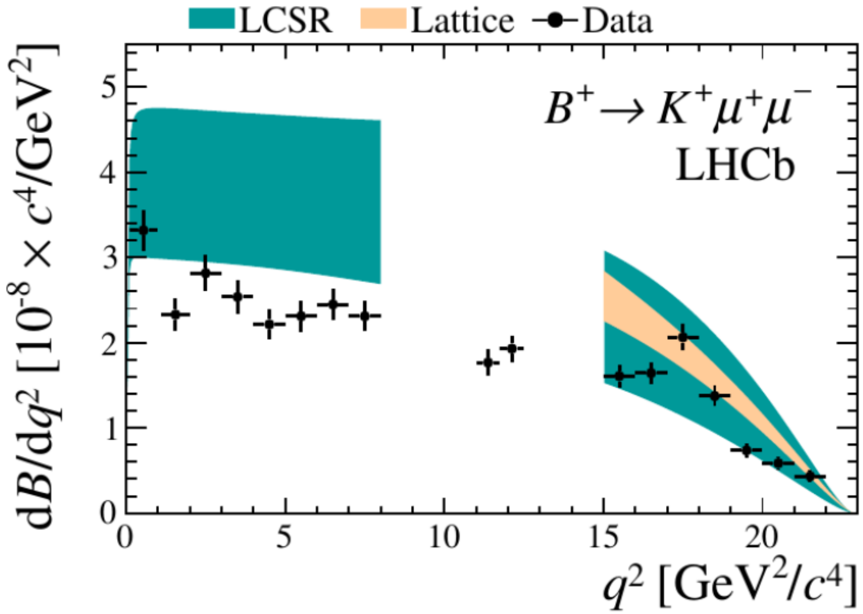
* The most significant effect occurs in a bin extending well above the perturbative charm threshold, outside the range of validity of the theory framework

SM starting to crack?

Reduced Branching Ratios

Altmannshofer

LHCb Collaboration 1305.2168, 1403.8044



$B \to K^*\mu^+\mu^-$, $B \to K\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$ branching ratio measurements seem systematically below SM predictions

SM starting to crack?

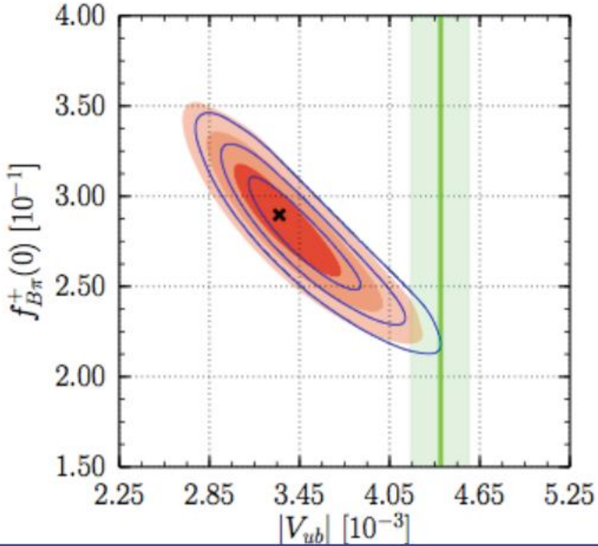
Mannel

Determination of $|V_{ub}|$

fit of LCSR with the combined BaBar/Belle data at $0 < q^2 < 12\ \mathrm{GeV}^2$

$$(2010):\ |V_{ub}| = \left(3.43^{+0.27}_{-0.23}\right) \cdot 10^{-3}$$

$$(2013):\ |V_{ub}| = \left(3.32^{+0.26}_{-0.22}\right) \cdot 10^{-3}$$



blue lines: 68%, 95%, 99% prob. contours for 2010 data
red area: 68%, 95%, 99% prob. contours for 2013 data

green line/area - inclusive determination:
central value / 68% CL interval for GGOU/HFAG

SM starting to crack?

$|V_{cb}|$ summary

Ricciardi

Exclusive decay	$|V_{cb}| \times 10^3$
$\bar{B} \to D^* l \bar{\nu}$	
FNAL/MILC (Lattice unquenched 2014)	$39.04 \pm 0.49_{\rm exp} \pm 0.53_{\rm QCD} \pm 0.19_{\rm QED}$
HFAG (Lattice unquenched 2012)	$39.54 \pm 0.50_{\rm exp} \pm 0.74_{\rm th}$
Rome (Lattice quenched $\omega \neq 1$ 2008)	$37.4 \pm 0.5_{\rm exp} \pm 0.8_{\rm th}$
HFAG (Sum Rules 2012)	$41.6 \pm 0.6_{\rm exp} \pm 1.9_{\rm th}$
$\bar{B} \to D l \bar{\nu}$	
FNAL/MILC (Lattice unquenched $\omega \neq 1$ 2013)	$38.50 \pm 1.9_{\rm exp+lat} \pm 0.2_{\rm QED}$
PDG (HQE + BPS 2012)	$40.6 \pm 1.5_{\rm exp} \pm 0.8_{\rm th}$
Rome (Lattice quenched $\omega \neq 1$ 2009)	$41.6 \pm 1.8 \pm 1.4 \pm 0.7_{FF}$
Inclusive decays	
HFAG ($B_s \to X_s \gamma$ constraint)	$41.94 \pm 0.43_{\rm fit} \pm 0.59_{\rm th}$
HFAG (m_c constraint)	$41.88 \pm 0.44_{\rm fit} \pm 0.59_{\rm th}$
Gambino, Schwanda 2014	42.42 ± 0.86

3σ disagreement

Future:

- CLEO →≈50-70 more stat B factories →≈50 more stat Belle II
- LHCb: about 5 million $B \to D^* \mu \nu$ decay no prospects for $|V_{cb}|$ measurement

SM starting to crack?

Hurth

Signs for lepton non-universality ?

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$

LHCb; arXiv:1406.6482

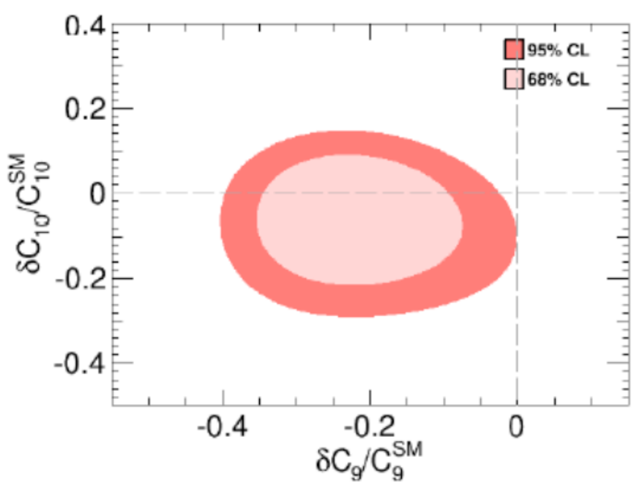
2.6σ deviation from SM

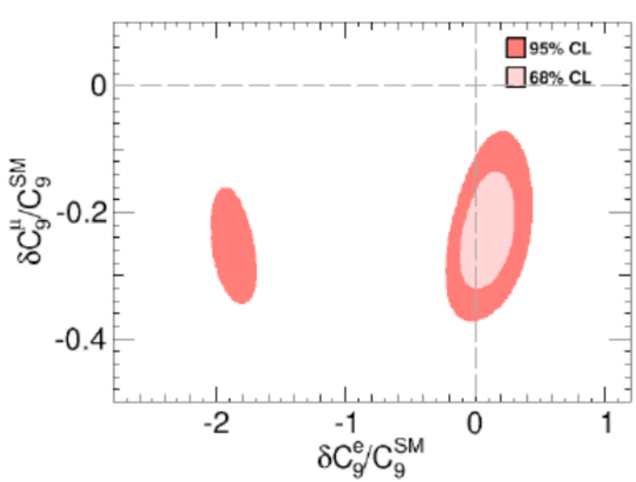
Hiller,Schmaltz; Ghosh et al.; Biswas et al.; Straub et al.;Hurth et al.;Glashow et al.

Global fits to the $b \to s\ell\ell$ data

Hurth,Mahmoudi,Neshatpour,arXiv:1410.4545

Fit results for two operators





From hints to discovery

- Many checks and tests remain
  - Power corrections
  - Long-distance QCD
  - Charm threshold
- More data
  - Belle II: 50-75 ab^{-1} luminosity anticipated by 2021
    - About 100× luminosity of Belle or BaBar

Still more data-mining

S. Jäger

"Clean" angular observables

Useful to consider functions of the angular coefficients for which form factors drop out in the heavy quark limit if perturbative QCD corrections neglected.

Becirevic, Schneider 2011
Matias, Mescia, Ramon, Virto 2012
Descotes-Genon et al 2012
(also Krueger,Matias 2005; Egede et al 2008)

E.g.

neglecting strong phase differences [tiny; take into account in numerics]

$$P_1 \equiv \frac{I_3 + \bar{I}_3}{2(I_{2s} + \bar{I}_{2s})} = \frac{-2\,\mathrm{Re}(H_V^+ H_V^{-*} + H_A^+ H_A^{-*})}{|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2} = 0,$$

$$P_3^{CP} \equiv -\frac{I_9 - \bar{I}_9}{4(I_{2s} + \bar{I}_{2s})} = -\frac{\mathrm{Im}(H_V^+ H_V^{-*} + H_A^+ H_A^{-*})}{|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2} = 0,$$

(Melikhov 1998)
Krueger, Matias 2002
Lunghi, Matias 2006
Becirevic, Schneider 2011

$$P_5' = \frac{\mathrm{Re}[(H_V^- - H_V^+)H_A^{0*} + (H_A^- - H_A^+)H_V^{0*}]}{\sqrt{(|H_V^0|^2 + |H_A^0|^2)(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2)}} = \frac{C_{10}\,(C_{9,\perp} + C_{9,\parallel})}{\sqrt{(C_{9,\parallel}^2 + C_{10}^2)(C_{9,\perp}^2 + C_{10}^2)}}$$

in SM, neglecting power corrections and pert. QCD corrections

where $C_{9,\perp} = C_9^{\mathrm{eff}}(q^2) + \frac{2\,m_b\,m_B}{q^2}\,C_7^{\mathrm{eff}}$

$C_{9,\parallel} = C_9^{\mathrm{eff}}(q^2) + \frac{2\,m_b\,E}{q^2}\,C_7^{\mathrm{eff}}$

C_7 and C_9 opposite sign
destructive interference enhances vulnerability to anything that violates the large-energy form factor relations

much more relevant to P_5' (and others) than to P_1 or P_3^{CP}

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Still more precision calculations

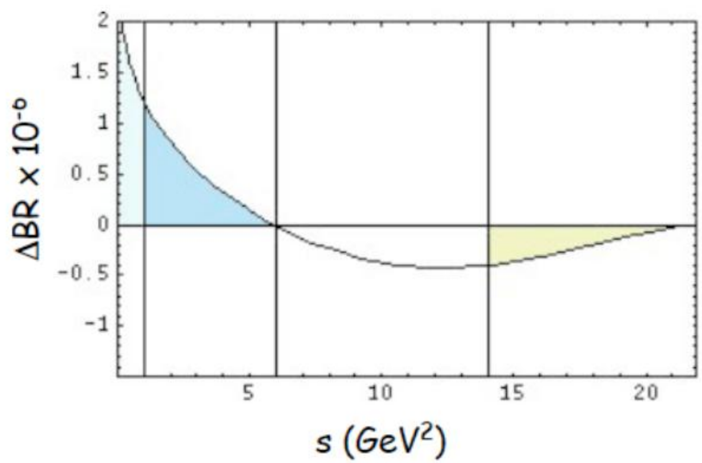
Latest improvements of inclusive $\bar{B} \to X_s \ell^+ \ell^-$

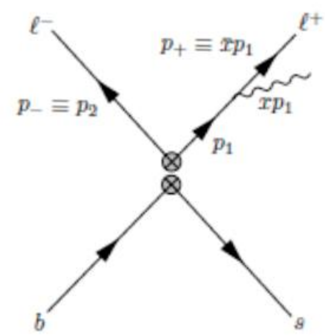
Hurth

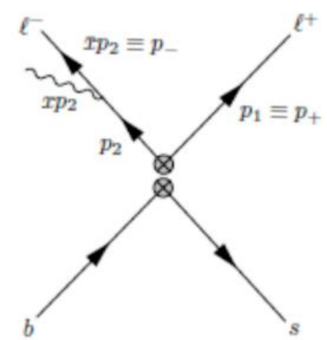
Beyond existing NNLL QCD precision electromagnetic corrections were calculated: Huber,Hurth,Lunghi,Nucl.Phys.B802(2008)40 and work in progress

Corrections to matrix elements lead to large collinear $Log(m_b/m_\ell)$

$$\delta \mathrm{BR}(B \to X_s \mu^+ \mu^-) = \begin{cases} (+2.0\%) & \text{low } q^2 \\ (-6.8\%) & \text{high } q^2 \end{cases} \quad \delta \mathrm{BR}(B \to X_s e^+ e^-) = \begin{cases} (+5.2\%) & \text{low } q^2 \\ (-17.6\%) & \text{high } q^2 \end{cases}$$







Still more precision calculations

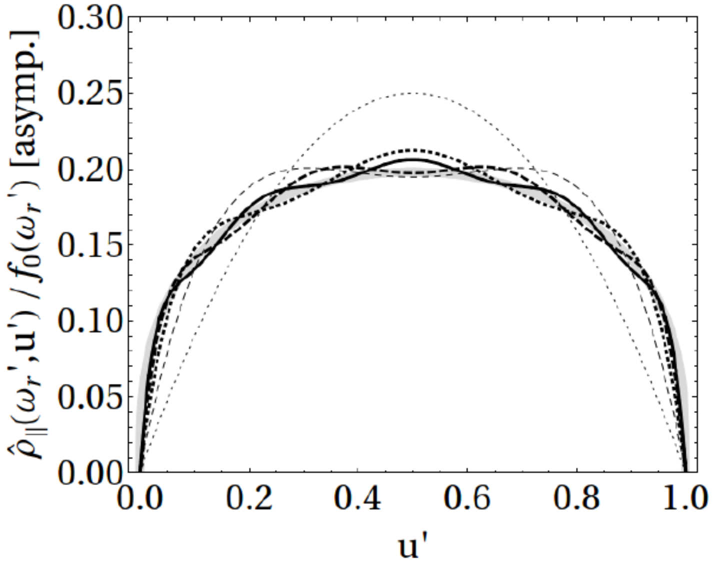
Asymptotic behaviour (Λ_b) [Bell/TF/Wang/Yip]

- Asymptotically, for $\mu \gg \mu_0$, the dependence on dual momentum fraction u' (approximately) approaches functional form

Feldmann

$$\hat{\rho}_2(\omega_r', u') \overset{\mu\to\infty}{\propto} f_0(\omega_r', \mu)\, (u'\bar{u}')^{\sim 1/3}$$

- Dependence on reduced momentum ω_r' factorizes in that limit.



different levels of Gegenbauer truncation:

- $n = 0$ (thin dotted)
- $n = 2$ (thin dashed)
- $n = 4$ (thick dotted)
- $n = 6$ (thick dashed)
- $n = 8$ (solid)

gray band $\propto (u'(1-u'))^{1/3}$.

[see also Braun/Derkachov/Manashov '14]

Thinking of new physics

- Will discriminate NP models by patterns of deviations in observables

Two Simplest General Frameworks

Buras

MFV (CMFV) $U(3)^3$

(symmetry between 3 generations)

Stringent Correlations between K, B_s, B_d

No new sources of flavour and CP violation

$S_{\psi K_s} = \sin 2\beta \;,\quad S_{\psi\varphi} = S_{\psi\varphi}^{SM} = \text{small}$

No Right-handed currents

$U(2)^3$ Flavour Symmetry

(symmetry between two light generations)

Stringent Correlations between B_s and B_d

Correlations $K \leftrightarrow B_{s,d}$ absent

New sources of CP violation in B_s, B_d but

$S_{\psi K_s} \leftrightarrow S_{\psi\varphi}$ anticorrelated

Right-handed currents strongly suppressed

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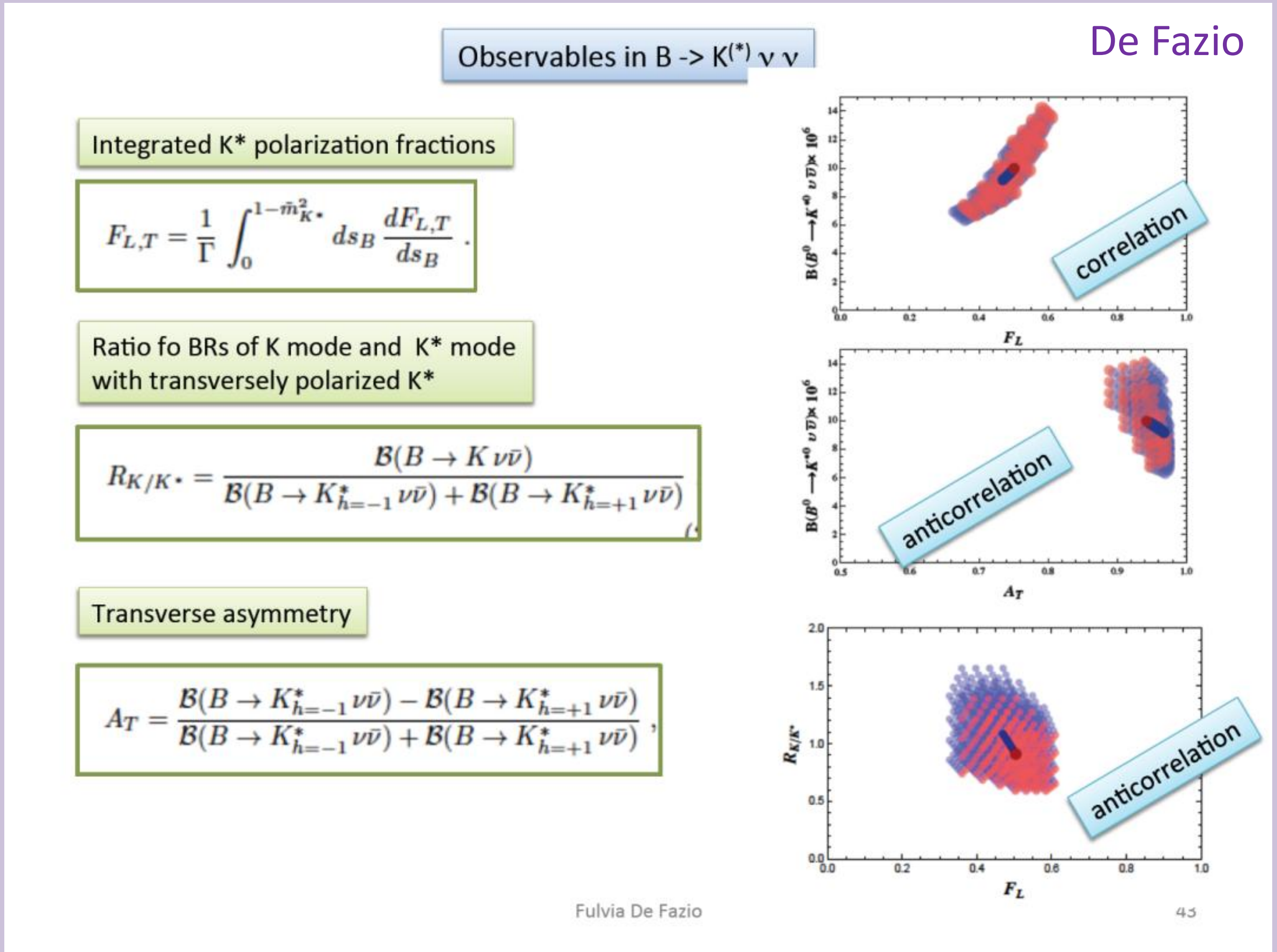
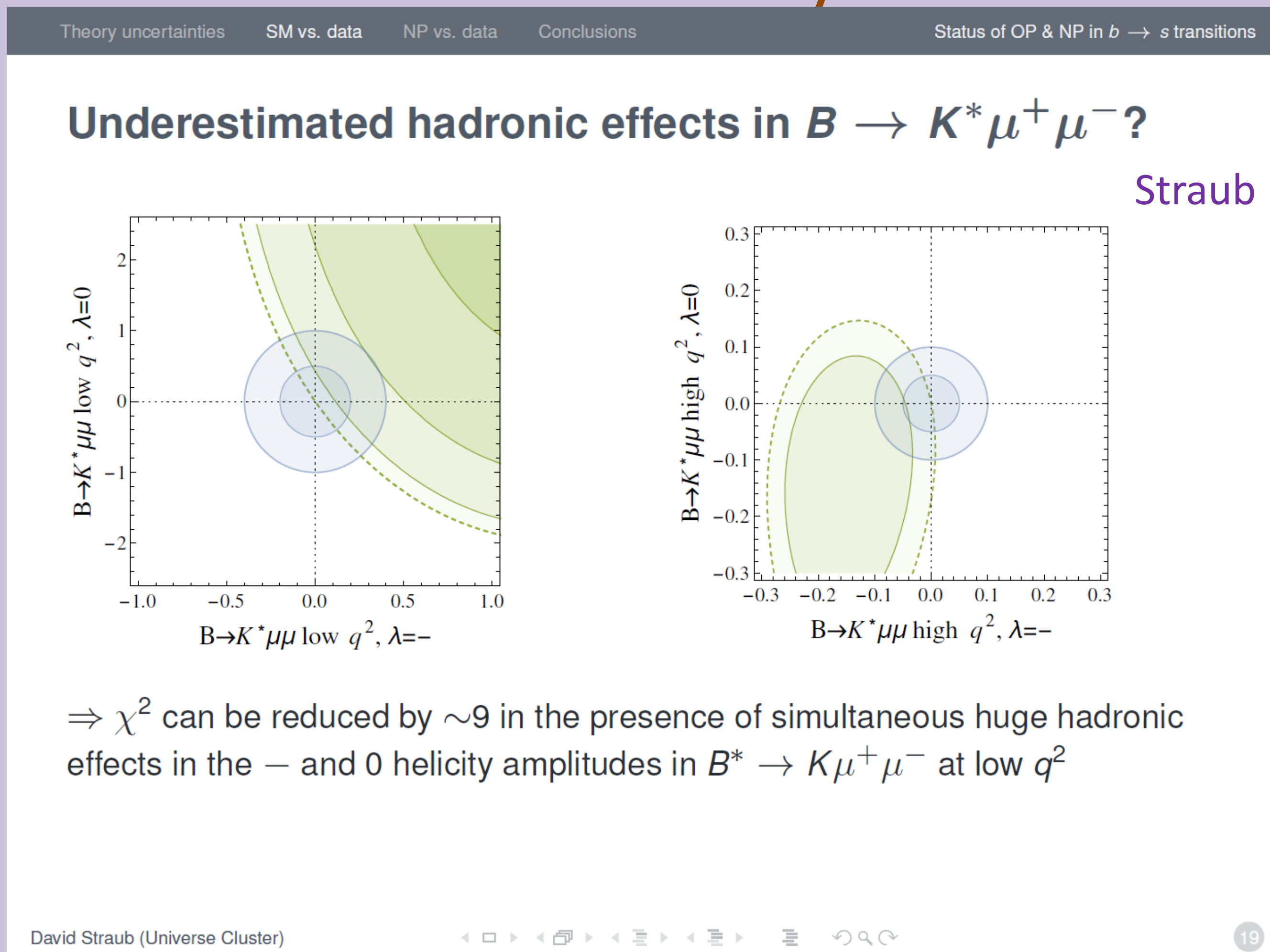
Thinking of new physics

- Will discriminate NP models by patterns of deviations in observables



Pattern recognition

- Correlations alleviate uncomfortable flat directions between NP effects and theory errors



Pattern recognition

- Correlations alleviate uncomfortable flat directions between NP effects and theory errors

Future tests of LFU

Straub

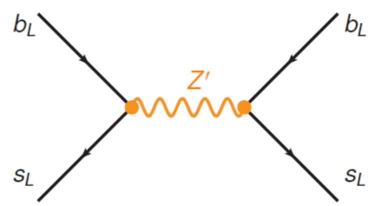
Spectacular deviations in $B \to K^* \mu^+ \mu^-$ vs $B \to K^* e^+ e^-$ angular observables and others can distinguish between different scenarios!

Observable	Ratio of muon vs. electron mode			
	$C_9^{NP} = -1.5$	-1.5	-0.7	-1.3
	$C_9' = 0$	0.8	0	0
	$C_{10}^{NP} = 0$	0	0.7	0.3
$10^7 \frac{dBR}{dq^2}(\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-)_{[1,6]}$	0.83	0.77	0.79	0.81
$10^7 \frac{dBR}{dq^2}(\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-)_{[15,22]}$	0.76	**0.69**	0.76	0.75
$A_{FB}(\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-)_{[4,6]}$	**0.18**	**0.10**	0.75	**0.27**
$S_5(\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-)_{[4,6]}$	**0.66**	**0.66**	0.93	0.71
$10^8 \frac{dBR}{dq^2}(B^+ \to K^+\ell^+\ell^-)_{[1,6]}$	0.75	0.82	0.77	0.74
$10^8 \frac{dBR}{dq^2}(B^+ \to K^+\ell^+\ell^-)_{[15,19]}$	0.75	0.83	0.77	0.75

Pattern recognition

- Concrete models allow full exploration of observables beyond typical QFV measurements

B_s Mixing



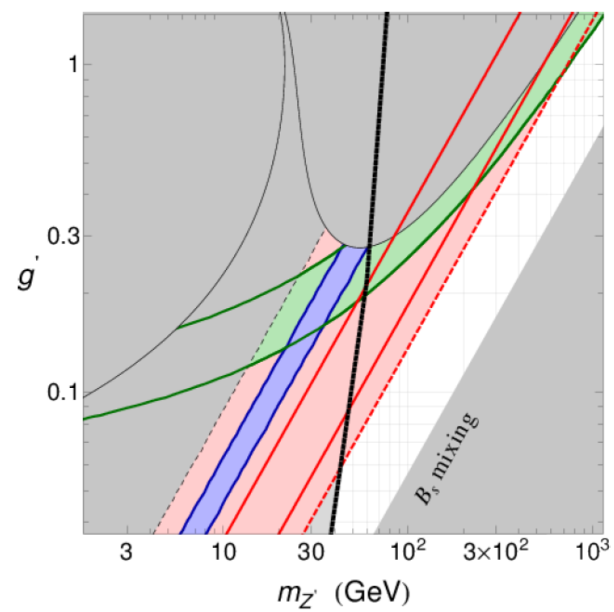
$$M_{12}^{NP} \propto (Y_{Qb} Y_{Qs}^*)^2 \frac{\langle \Phi \rangle^2}{m_Q^4}$$

B_s mixing leads to an upper bound on the $U(1)'$ breaking vev, if the Z' is to explain the $b \to s\mu^+\mu^-$ anomalies

$\langle \Phi \rangle \lesssim 1.8$TeV

might be possible to probe (parts of) the open parameter space with neutrino tridents at LBNE

(WA, Gori, Pospelov, Yavin 1406.2332)



WA, Gori, Pospelov, Yavin 1403.1269

Altmannshofer

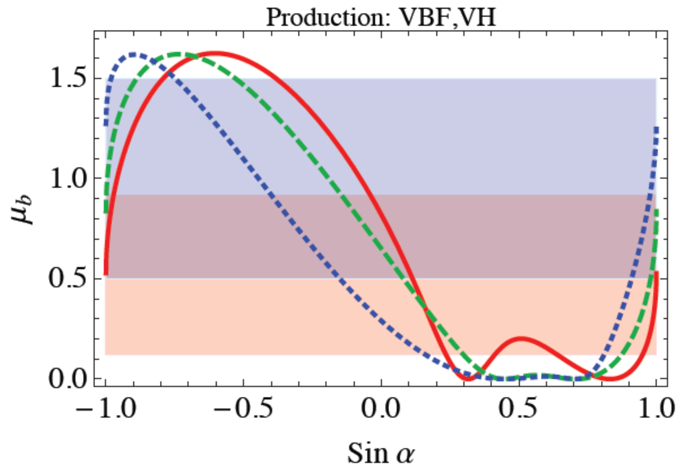
Pattern recognition

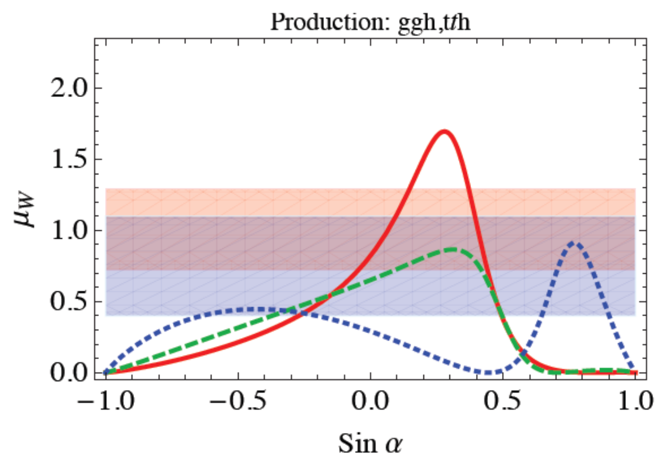
- Concrete models allow full exploration of observables beyond typical QFV measurements
- Flavor is intimately intertwined with collider physics and electroweak physics in the SM

Flavor model at the EW scale

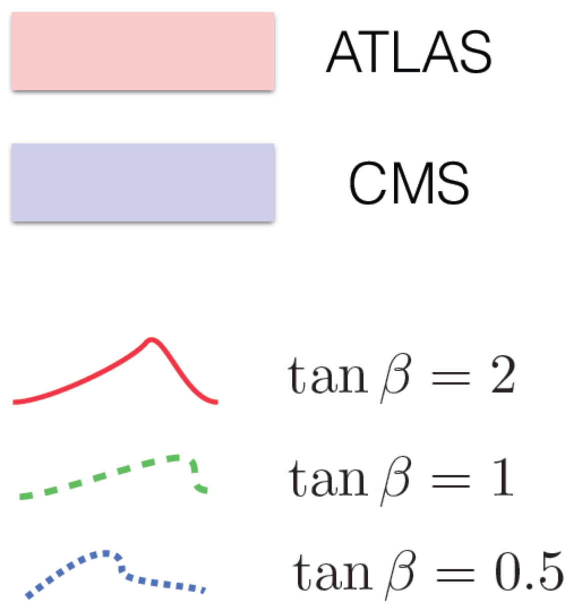
Bauer

Higgs couplings:





$$\mu_X = \frac{\sigma_{\text{prod}}}{\sigma_{\text{prod}}^{\text{SM}}} \frac{\Gamma_{h\to X}}{\Gamma_{h\to X}^{\text{SM}}} \frac{\Gamma_{h,\,\text{tot}}^{\text{SM}}}{\Gamma_{h,\,\text{tot}}}$$

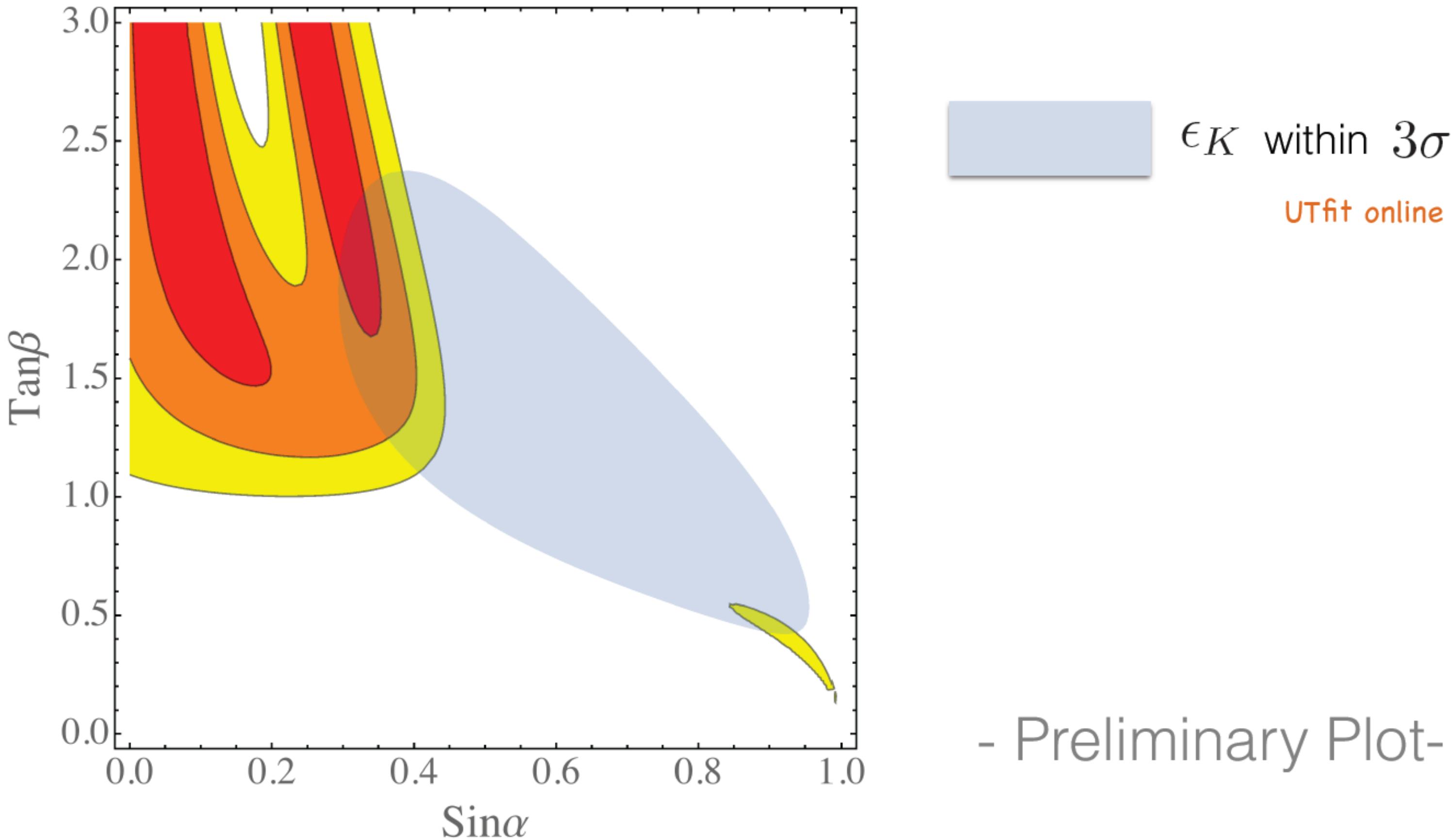


- Preliminary Plots-

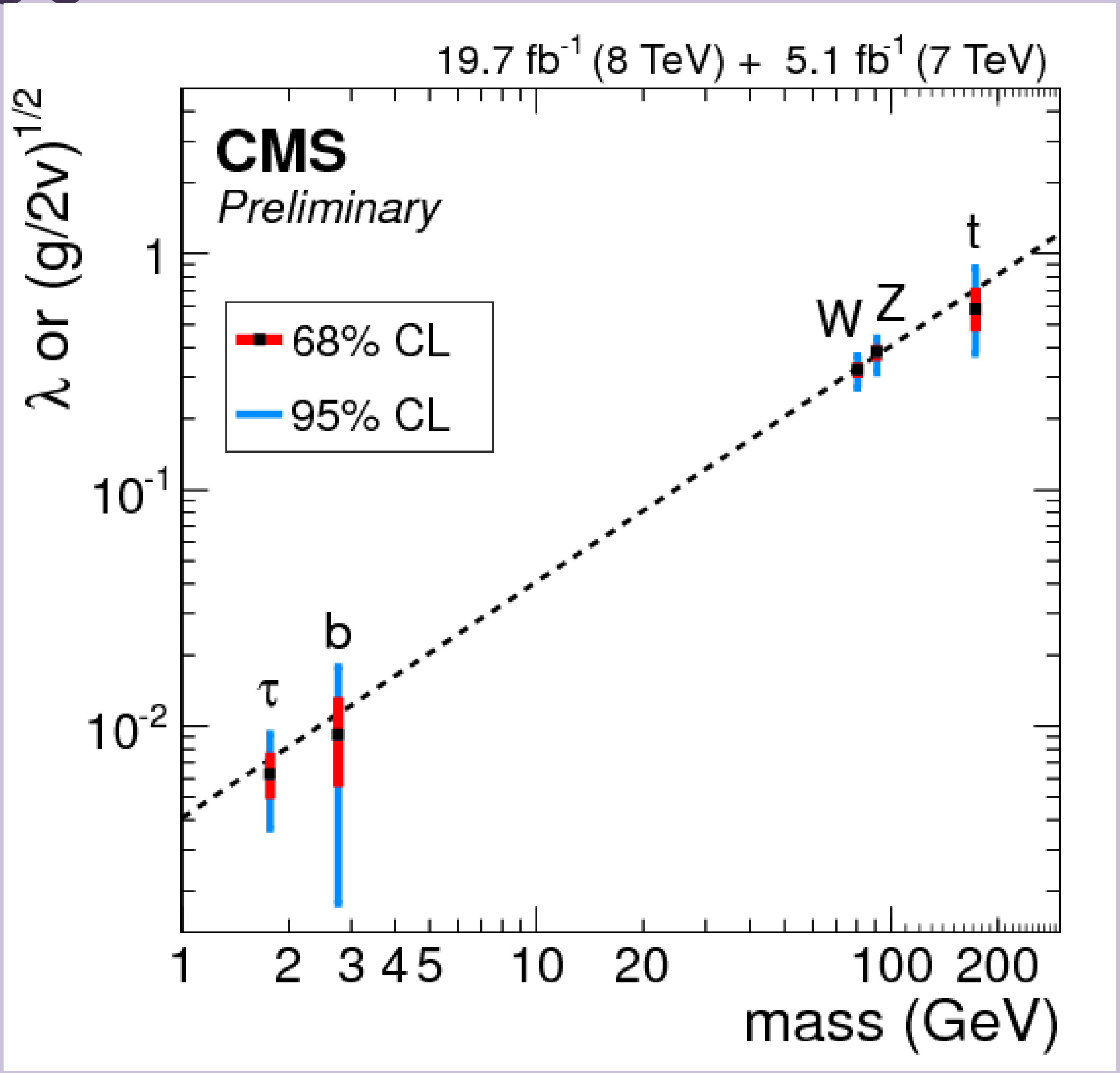
Flavor model at the EW scale

Bauer

Slightly tuned Yukawa couplings and including heavy Higgses



The Higgs as a Flavor Anchor

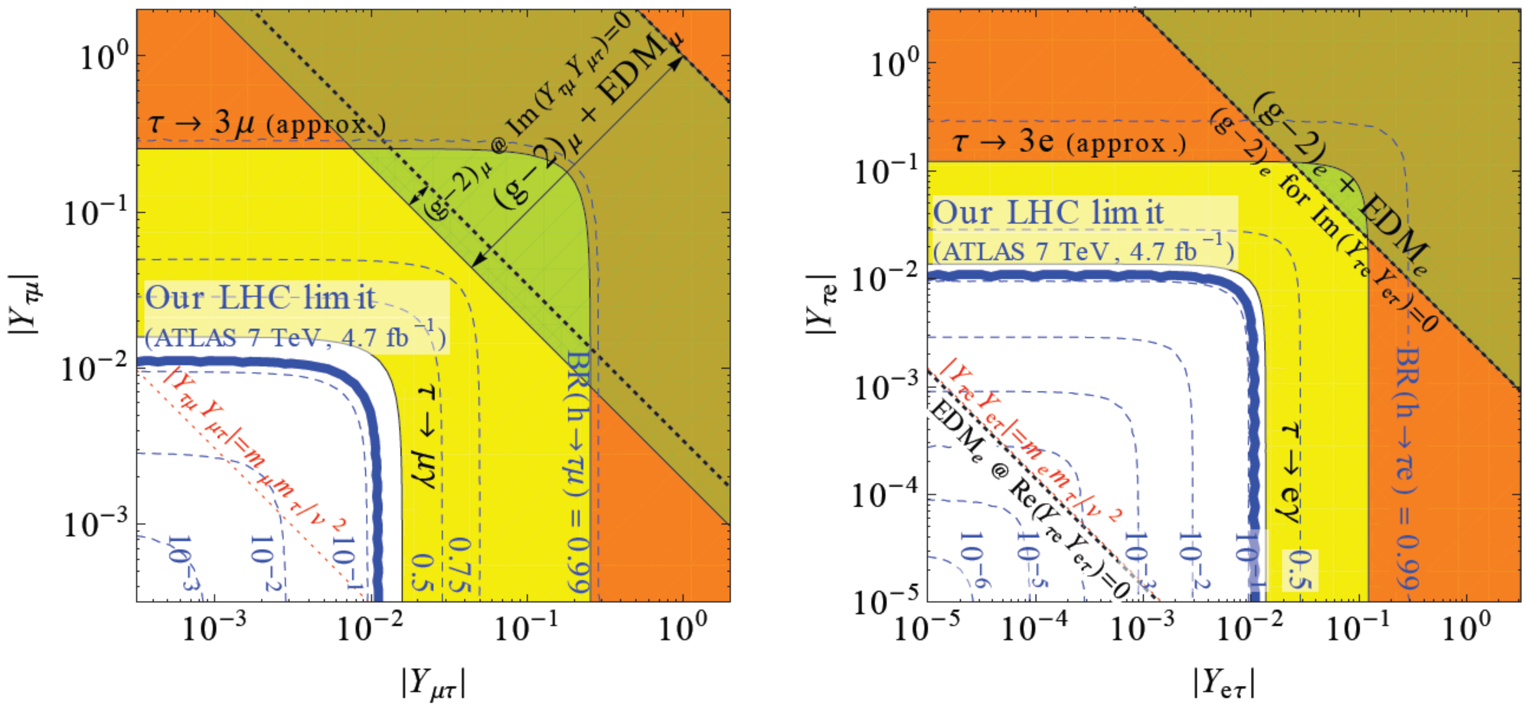


CMS-PAS-HIG-14-009

The Higgs as a flavor violation probe

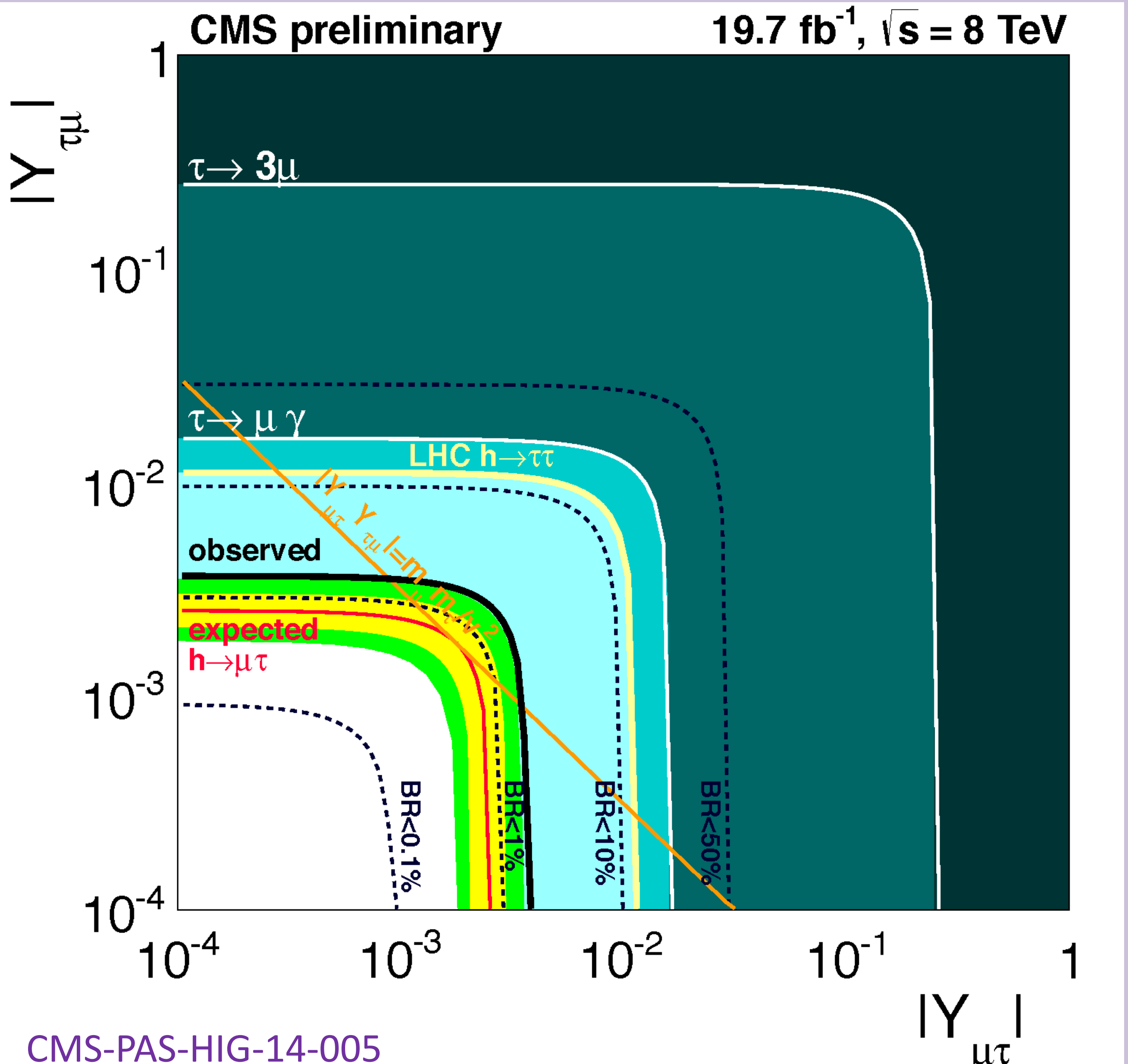
LHC constraints on $h \to \tau\mu$ and $h \to \tau e$

Kopp



Harnik JK Zupan, arXiv:1209.1397

The Higgs as a flavor violation probe

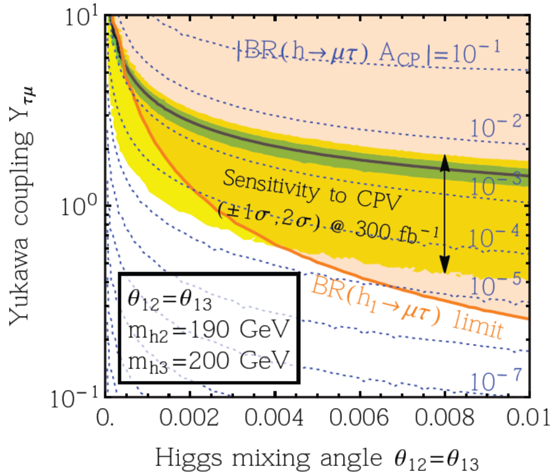


CMS-PAS-HIG-14-005

The Higgs as a CPV probe

Sensitivity to CPV in FCNC Higgs decays @ HL-LHC

Kopp



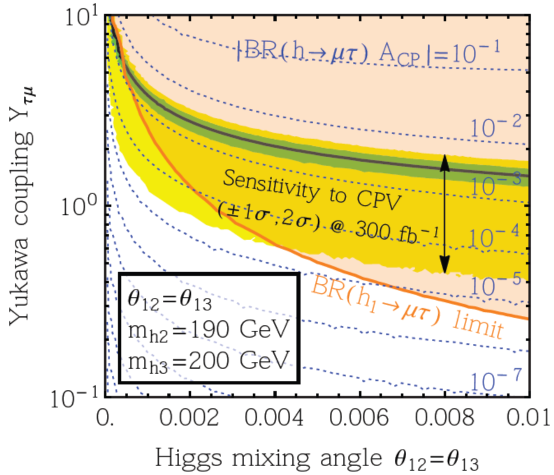
- Best discovery potential in small Higgs mixing regime
- CP violation visible only at high-luminosity LHC
- Would require a detection of $h \to \tau\mu$ or $h \to \tau e$ very soon.

JK Nardecchia, arXiv:1406.5303

The Higgs as a CPV probe

Sensitivity to CPV in FCNC Higgs decays @ HL-LHC

Kopp



- Best discovery potential in small Higgs mixing regime
- CP violation visible only at high-luminosity LHC
- Would require a detection of $h \to \tau\mu$ or $h \to \tau e$ very soon.

JK Nardecchia

CPV sensitivity in $h \to \tau^+\tau^-$

τ_h efficiency	50%	70%
3σ	$L = 550$ fb^{-1}	$L = 300$ fb^{-1}
5σ	$L = 1500$ fb^{-1}	$L = 700$ fb^{-1}
Accuracy($L = 3$ ab^{-1})	$11.5°$	$8.0°$

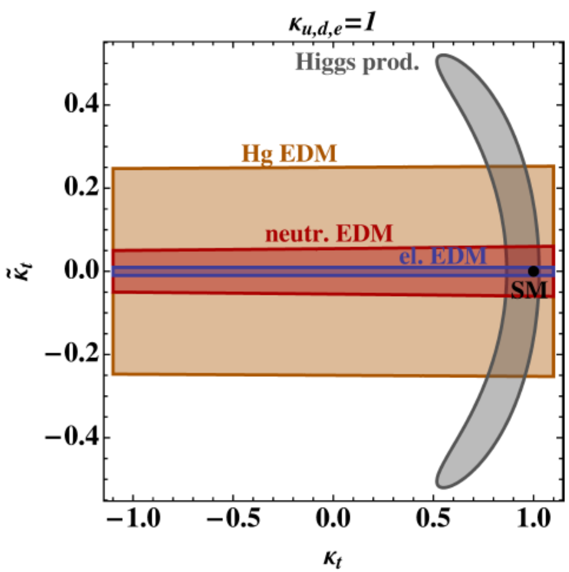
TABLE III: The luminosity required for distinguishing the scalar and pseudoscalar couplings and the accuracy in measuring Δ with 3 ab^{-1} of luminosity at the 14 TeV LHC.

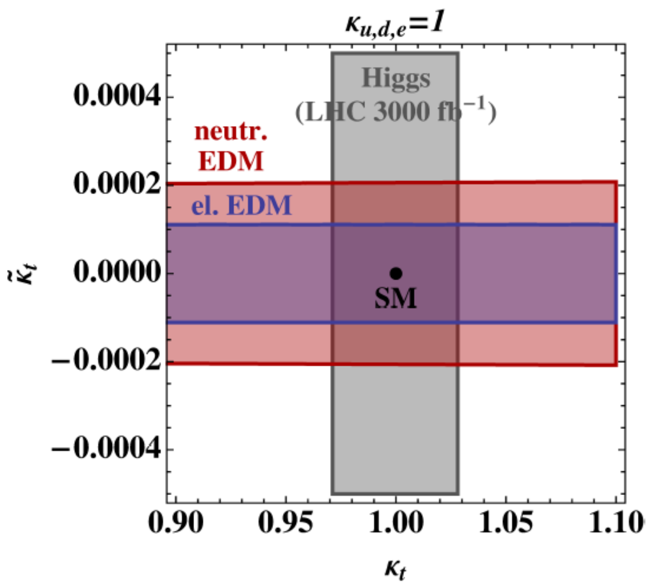
Harnik, Martin, Okui, Primulando, FY
PRD 88 (2013) 7, 076009 [arXiv:1308.1094]

The Higgs as a CPV probe

Combined constraints on top coupling

Brod





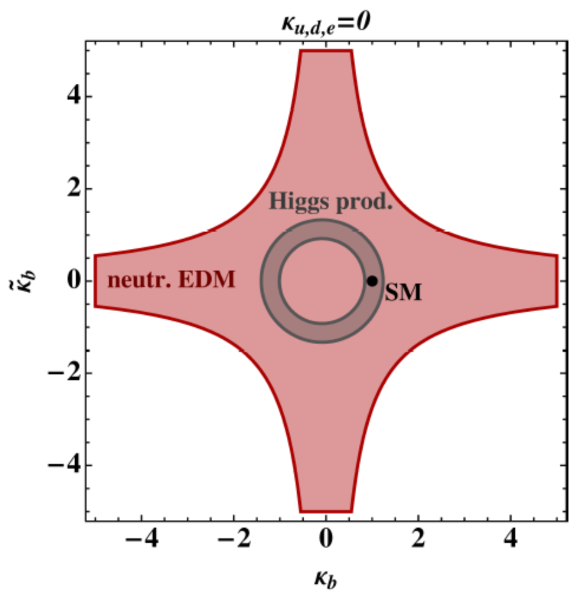
- Assume SM couplings to electron and light quarks
- Future projection for 3000fb^{-1} @ high-luminosity LHC
  [J. Olsen, talk at Snowmass Energy Frontier workshop]
- Factor 90 (300) improvement on electron (neutron) EDM
  [Fundamental Physics at the Energy Frontier, arXiv:1205.2671]

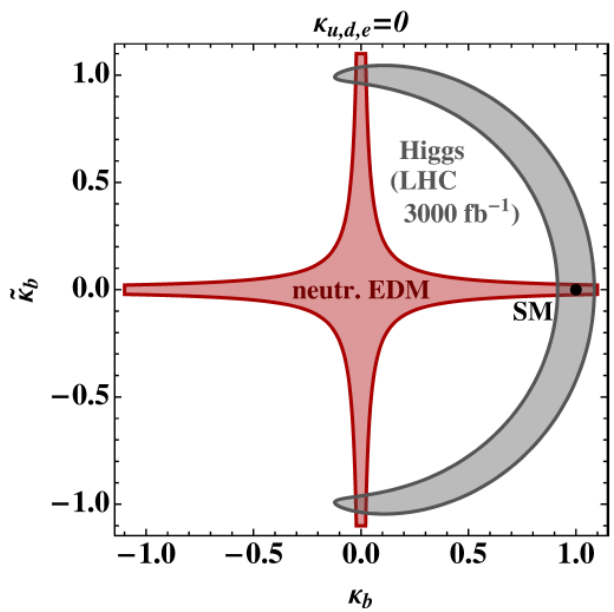
The Higgs as a CPV probe

Combined constraints on bottom couplings

Brod

- Set couplings to electron and light quarks to zero
- Contribution of Weinberg operator will lead to competitive constraints in the future scenario





The Higgs as the SM Anchor

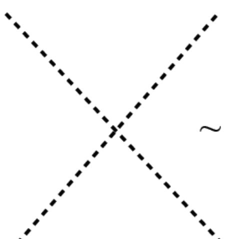
- Central role of the SM Higgs
  - Unitarize longitudinal gauge boson scattering

Effects of unitarity on couplings

El Hedri

$$\mathrm{Re}\,\mathrm{T}_{ii} < \frac{1}{2}$$

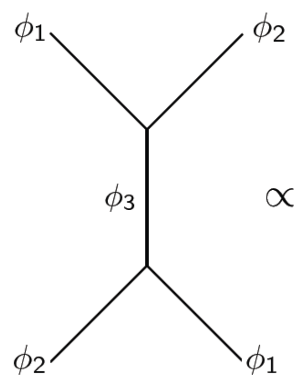
Dimensionless Unitarity



$$\sim \lambda^2$$

Bounds on quartic couplings
Lee, Quigg, Thacker [Phys. Rev. D 16, 1519 (1977)]

Dimensionful Unitarity



$$\propto \frac{A_{123}^2}{s - m_{\phi_3^2}}$$

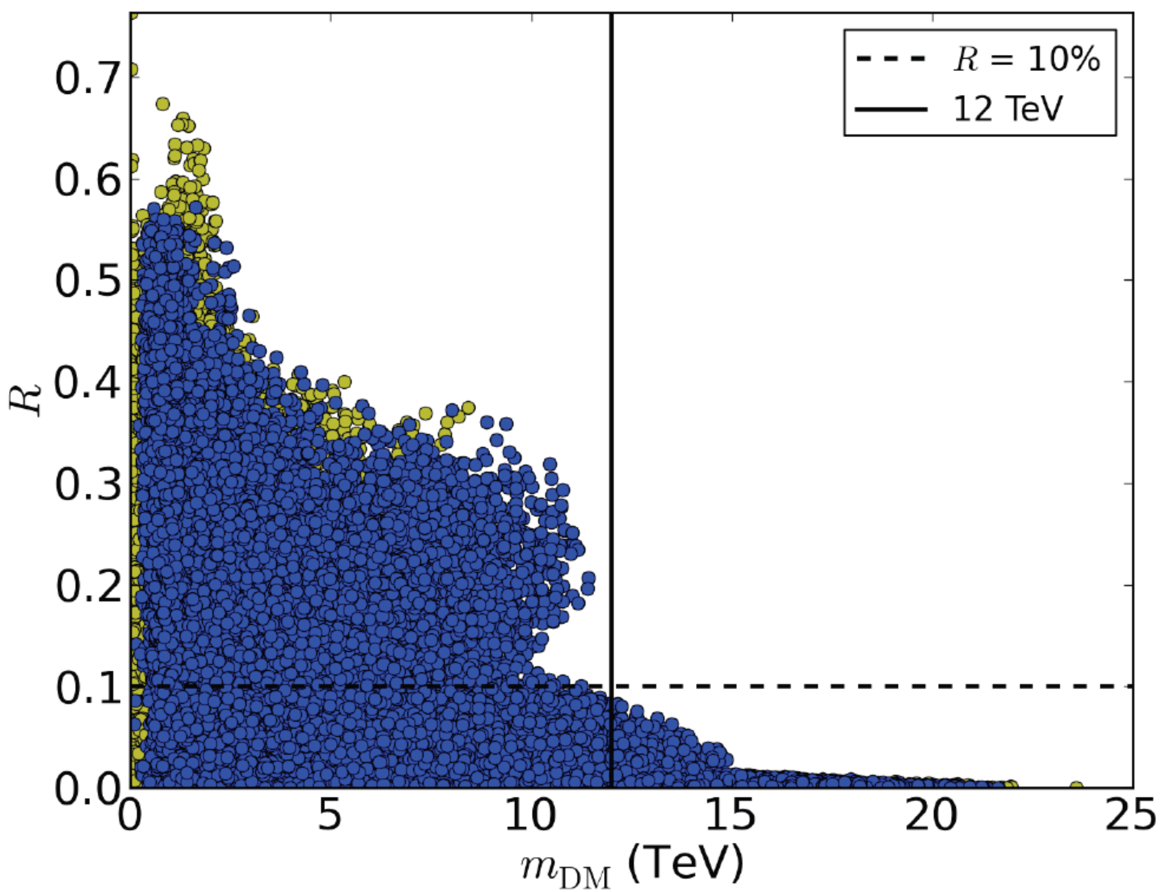
Bounds on mass ratios
Schuessler, Zeppenfeld [arXiv:0710.5175]

8 / 40

Unitarization and NMSSM dark matter

Results: Dark Matter

El Hedri



- Fine Tuning Factor $R = \min_i \frac{|2m_{\mathrm{DM}} - m_{H_i}|}{m_{H_i}}$

The Higgs as the SM Anchor

- Central role of the Higgs
  - Unitarize longitudinal gauge boson scattering
  - Breaks chiral $SU(2)_L$ symmetry, gives masses to charged fermion masses
  - Not yet determined to be the SM Higgs
    - To move forward, either compute in concrete models, simplified models, or an EFT

The Higgs as the SM Anchor

- Crucially important for the EFT to be precise and complete for data interpretation

The fundamental Higgs EFT is...

- NONLINEAR. Even when the Higgs mechanism and doublet is present.

Trott

- The right EFT has to reproduce the IR of the UV theory, and gravity introduces nonlinearities due to the singlet higgs field mixing with a scalar gravity component proportional to

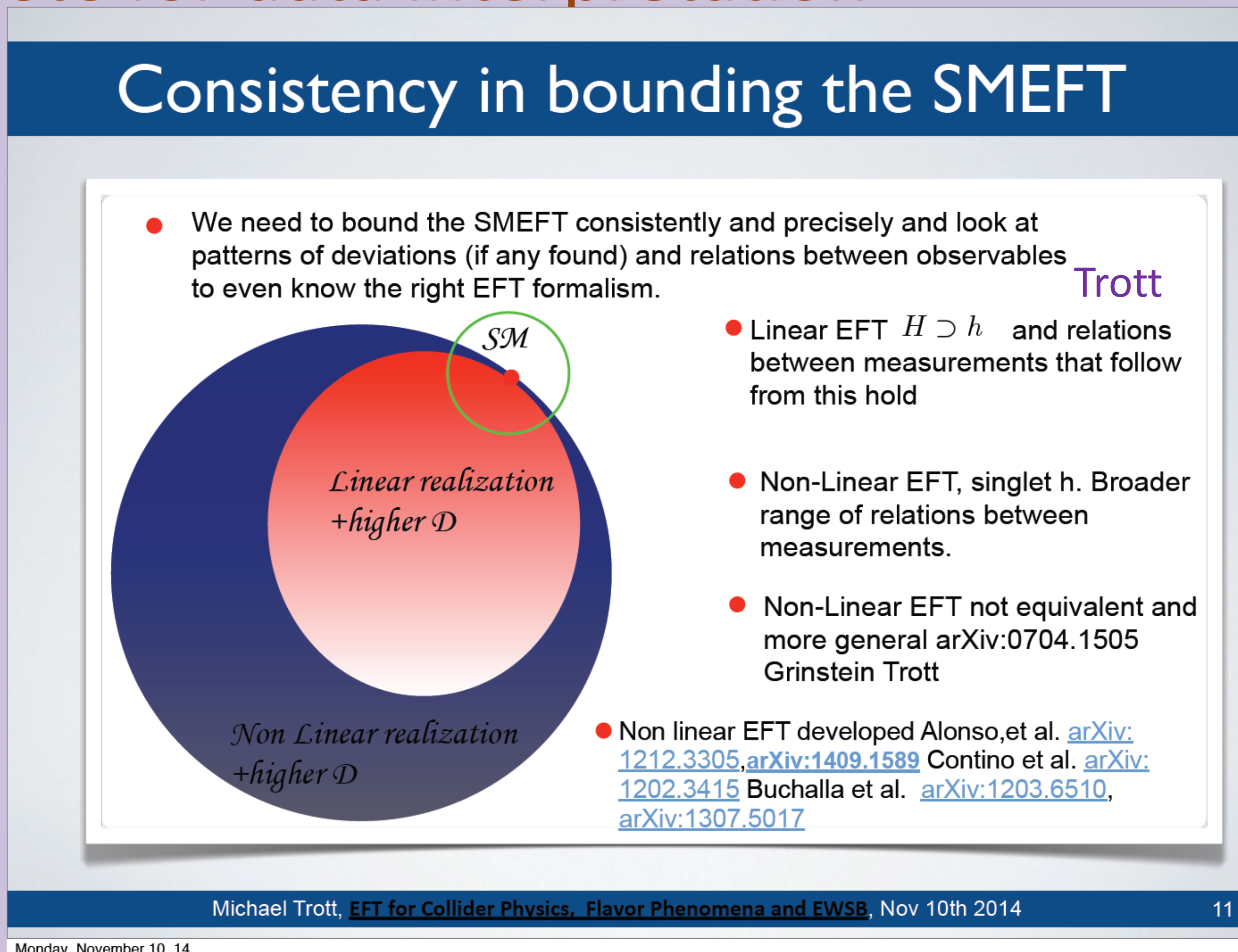
$$\xi \, \frac{\bar{X}}{M_{pl}}$$

- The question is not is the Higgs doublet or mechanism present.
  The question is “do we have interactions in the UV that force us to use a nonlinear formalism to reproduce the IR”.

- Note that convergence on SM values of couplings implies the cut off scale is parametrically separated from the ew vev scale, not a linear EFT.

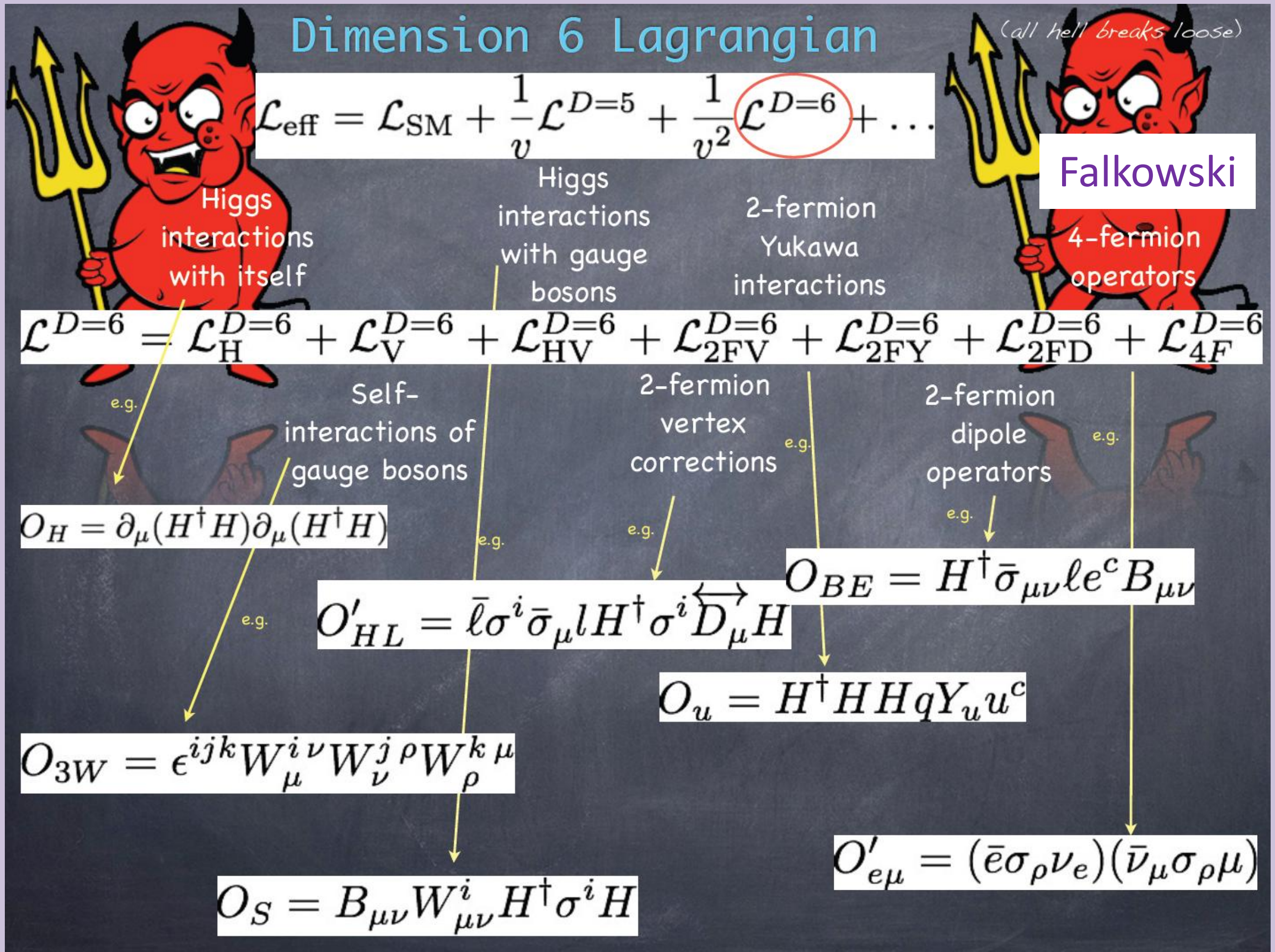
The Higgs as the SM Anchor

- Crucially important for the EFT to be precise and complete for data interpretation



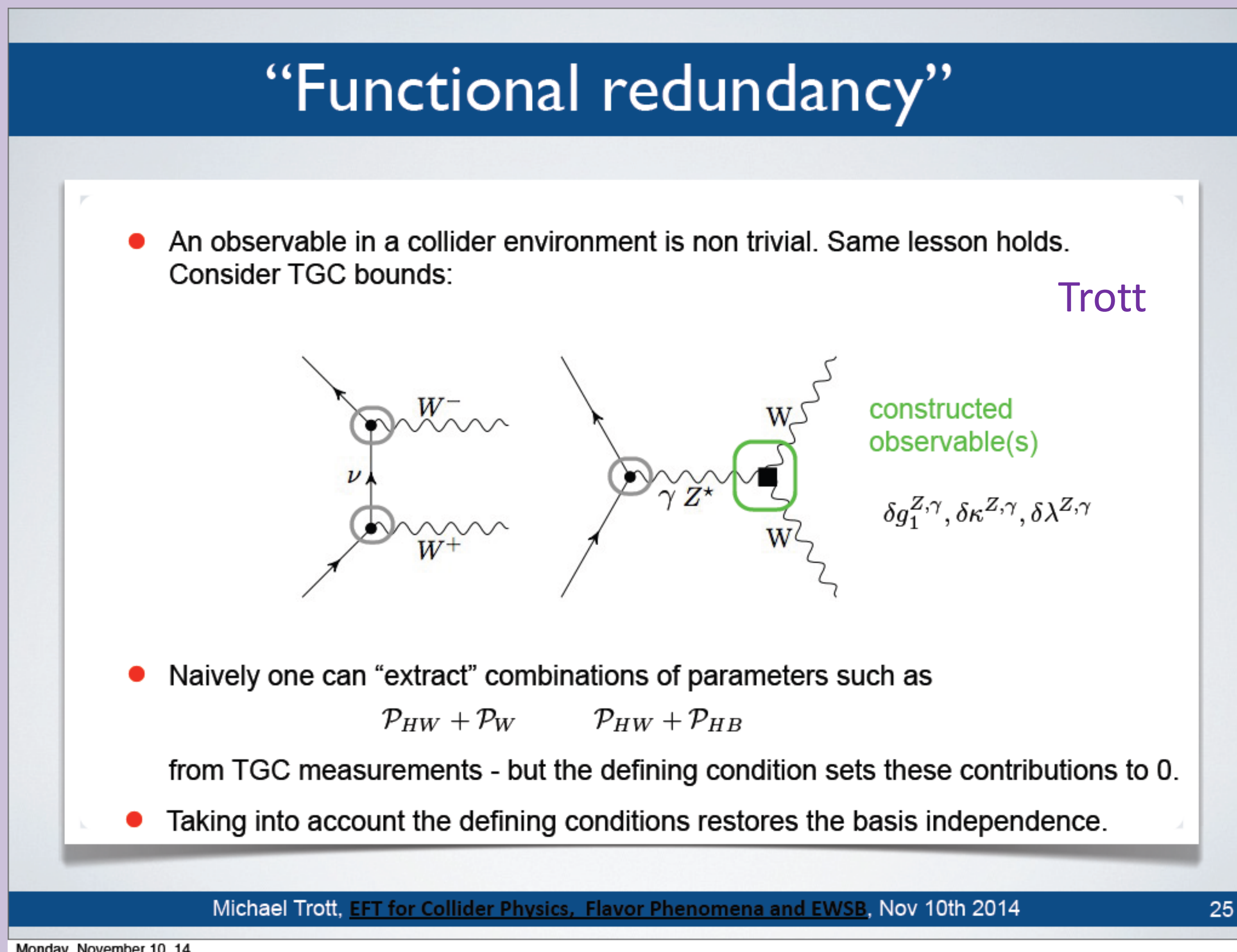
The Higgs as the SM Anchor

- SM-EFT to dimension 6 covers flavor, EW observables, Higgs physics



The Higgs as the SM Anchor

- Interplay with EW observables must be self-consistent!



The Higgs as the SM Anchor

- Interplay with EW observables must be self-consistent! But still promising attack of the SM-EFT

VV production constraints

- 11 parameters affecting WW and WZ production at linear level (previous 10 plus O3W which affects only TGCs)
- However, 8 combinations of these 11 parameters are already constrained by pole measurements
- Precision of WW measurements is only O(1)% in LEP and O(10%) in LHC, compared with O(0.1%) precision of LEP measurement of leptonic vertex corrections and oblique corrections
- Thus, these 8 EFT directions constrained by pole measurements are hardly relevant for WW and WZ measurements, given existing constraints
- We can use a simplified treatment of WW and WZ production, with only 3 free parameters

Falkowski

The Higgs as the SM Anchor

- Interplay with EW observables must be self-consistent! But still promising attack of the SM-EFT

VV produc

- 11 parameters affecting WW and
O3W which affects only TGCs)
- However, 8 combinations of these
measurements
- Precision of WW measurements i
compared with O(0.1%) precision
corrections and oblique correctio
- Thus, these 8 EFT directions cons
relevant for WW and WZ measur
- We can use a simplified treatmen
parameters

Falkowski

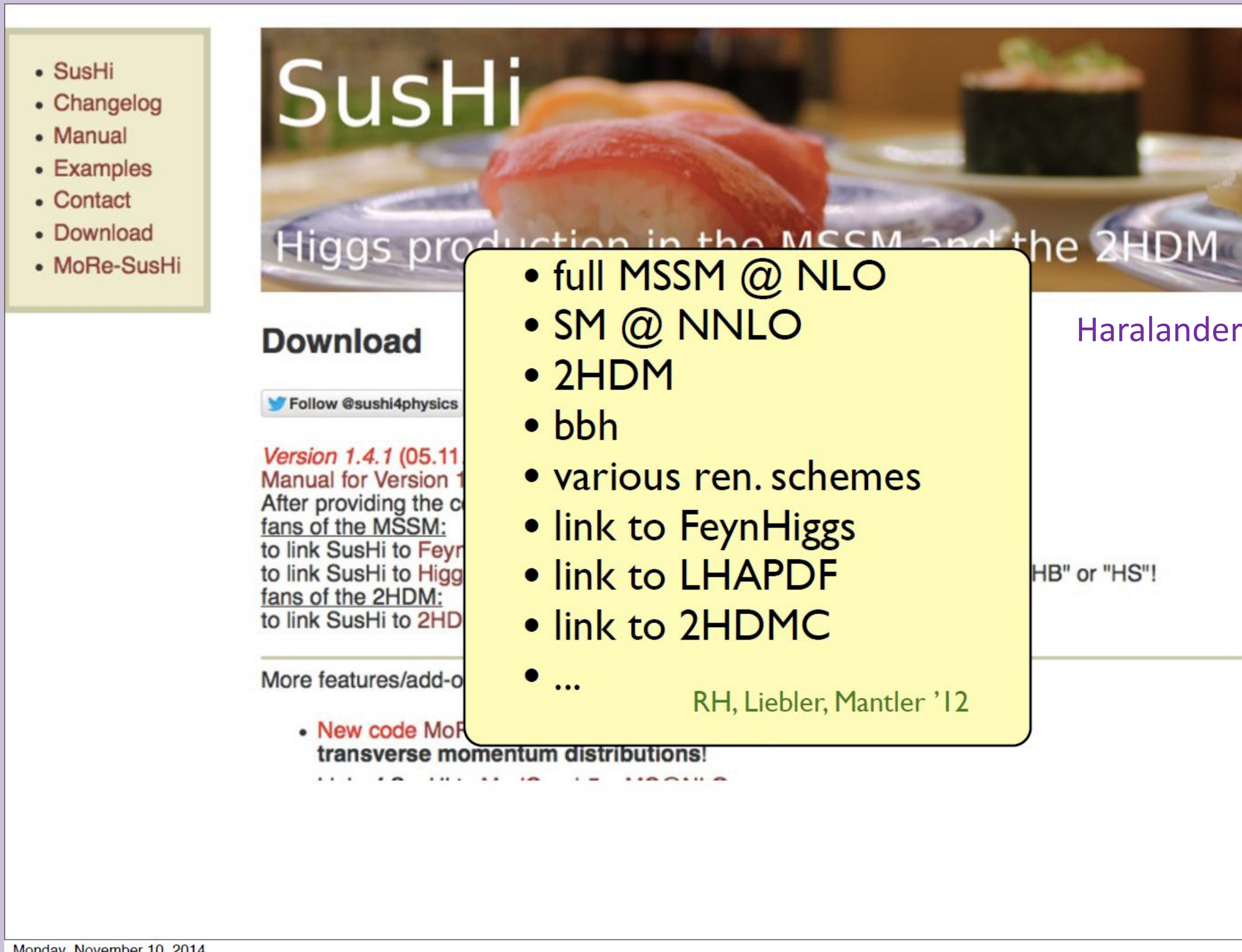
To take away

- There are strong constraints on certain combinations of dimension-6 operators from the pole observables measured at LEP-1 and other colliders
- WW production process is extremely important, because it lifts flat directions of the pole observables
- Current model independent LEP-2 constrain are weak, due to an accidental flat directions
- Better probes of dimension-6 operators in WW production should be designed for future e+e- colliders

Higgs Collider physics

- Central program of LHC Run 2
  - Experimental data thus far is disgustingly impressive
  - Must test Higgs via its decays, production modes, couplings, width, mass, branching fractions
- Ideal marketplace for crosstalk between theory and experiment

Precision calculations of Higgs xsecs



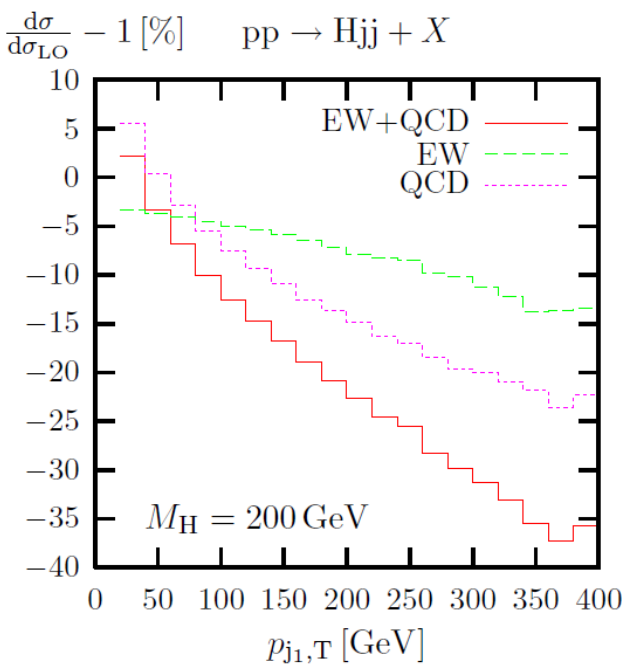
Precision calculations of Higgs xsecs

B. Jäger

Higgs production in VBF @ NLO EW

Ciccolini, Denner, Dittmaier (2007):
NLO EW corrections to inclusive cross sections and distributions

☞ NLO EW corrections non-negligible, modify K factors and distort distributions by up to 10%



publicly available parton-level Monte Carlo:
HAWK
[Denner, Dittmaier, Mück]

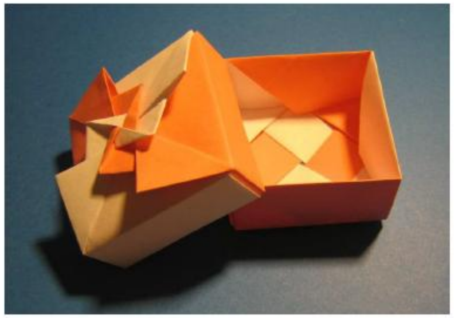
Precision calculations of EW xsecs

$VVjj$ matched with parton showers & NLO-QCD

B. Jäger

so far only implementation of EW- and QCD-induced $VVjj$ production processes available in the `POWHEG-BOX`:

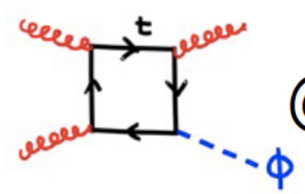
`http://powhegbox.mib.infn.it/`



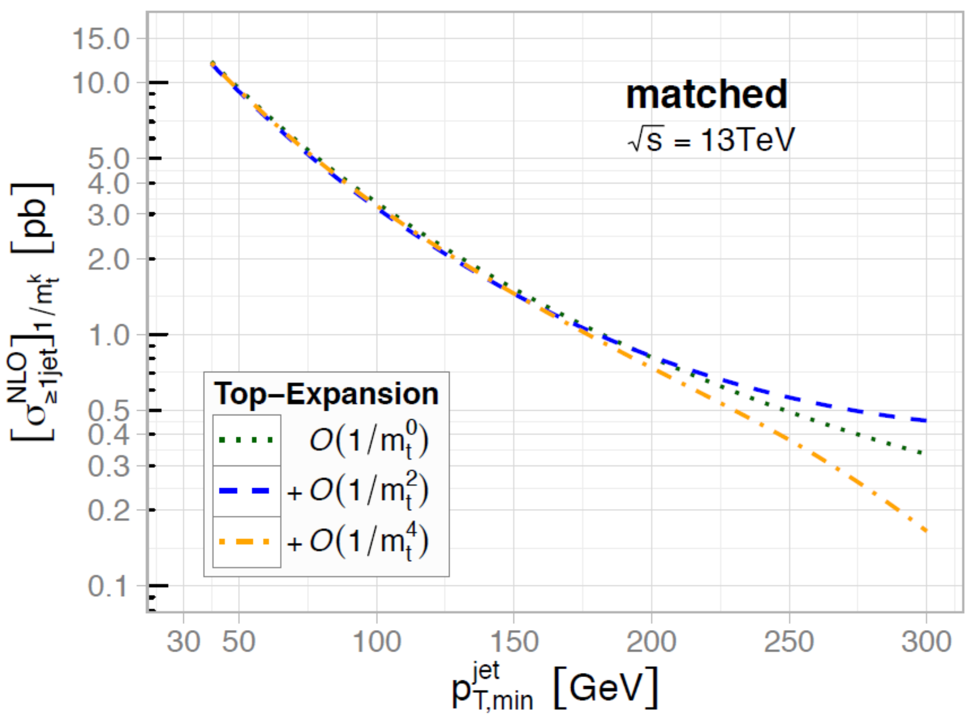
- QCD W^+W^+jj production *[Melia, Nason, Rontsch, Zanderighi (2011)]*
- EW W^+W^+jj production *[Zanderighi, B.J. (2011)]*
- EW W^+W^-jj production *[Zanderighi, B.J. (2013)]*
- EW $ZZjj$ production *[Karlberg, Zanderighi, B.J. (2013)]*

Need precise theory differential distributions

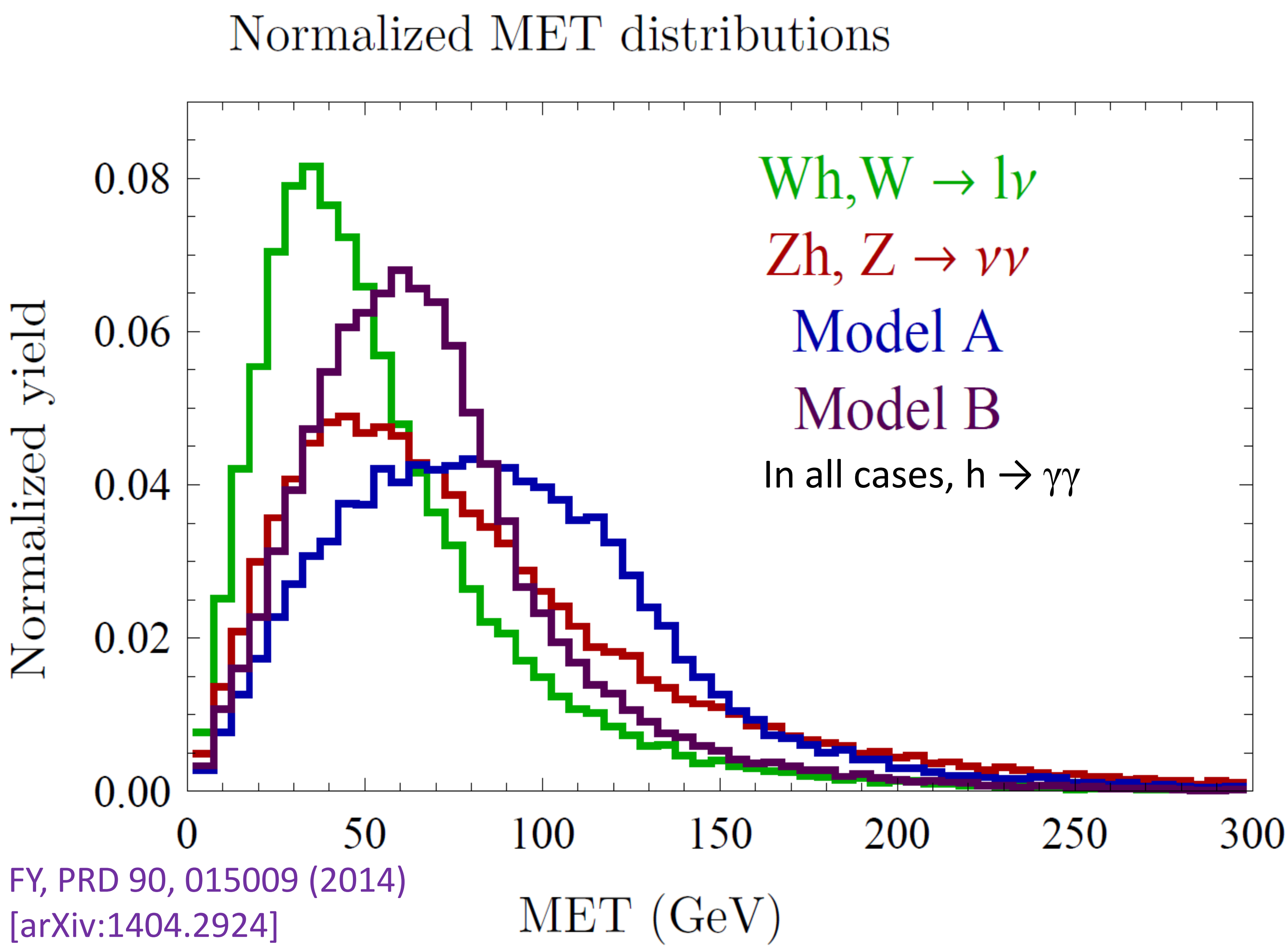
Haralander



@ NLO



Differential distributions powerful NP probe



FY, PRD 90, 015009 (2014)
[arXiv:1404.2924]

The stakes: the fate of the universe

Introduction

Goertz

Very important test:

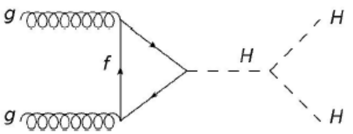
Higgs potential

self couplings

$$V(h) = \frac{1}{2} m_h^2 \, h^2 + \lambda_{hhh} v \, h^3 + \frac{1}{4} \lambda_{hhhh} \, h^4$$

λ_{hhh} can be measured in

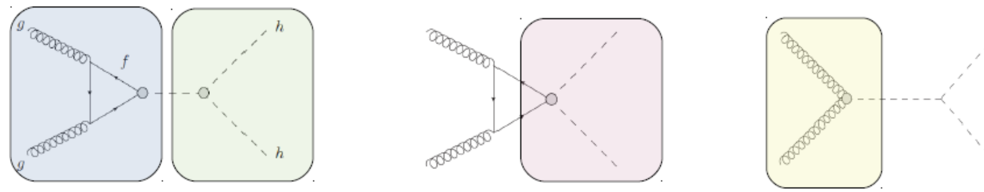
Higgs-pair production



The stakes: the fate of the universe

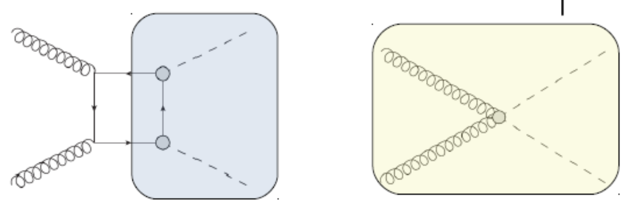
Cross Section in D=6 EFT

Goertz



$$\left.\frac{\mathrm{d}\hat\sigma(gg\to hh)}{\mathrm{d}\hat t}\right|_{\mathrm{EFT}} = \frac{G_F^2\alpha_s^2}{256(2\pi)^3}\Big\{\Big|C_\triangle F_\triangle(1-2c_H+c_t+c_6)+3F_\triangle(3c_t-c_H)\ +2c_gC_\triangle$$

$$+C_\Box F_\Box(1-c_H+2c_t)+2c_gC_\Box\Big|^2+\Big|C_\Box G_\Box\Big|^2\Big\}$$



$$C_\triangle = \frac{3m_h^2}{\hat s - m_h^2}, \qquad C_\Box = 1$$

$$F_\triangle = \frac{2}{3} + \mathcal{O}(\hat s/m_Q^2), \quad F_\Box = -\frac{2}{3} + \mathcal{O}(\hat s/m_Q^2),$$

$$G_\Box = \mathcal{O}(\hat s/m_Q^2)$$

Implemented in MC generator Herwig++

See Plehn, Spira, Zerwas ph/9603205

Normalize to NNLO: de Florian, Mazzitelli, 1309.6594

The stakes: the fate of the universe

Final Results

Goertz

Expected 1σ constraints at the 14 TeV LHC, assuming f_{th} = 30%

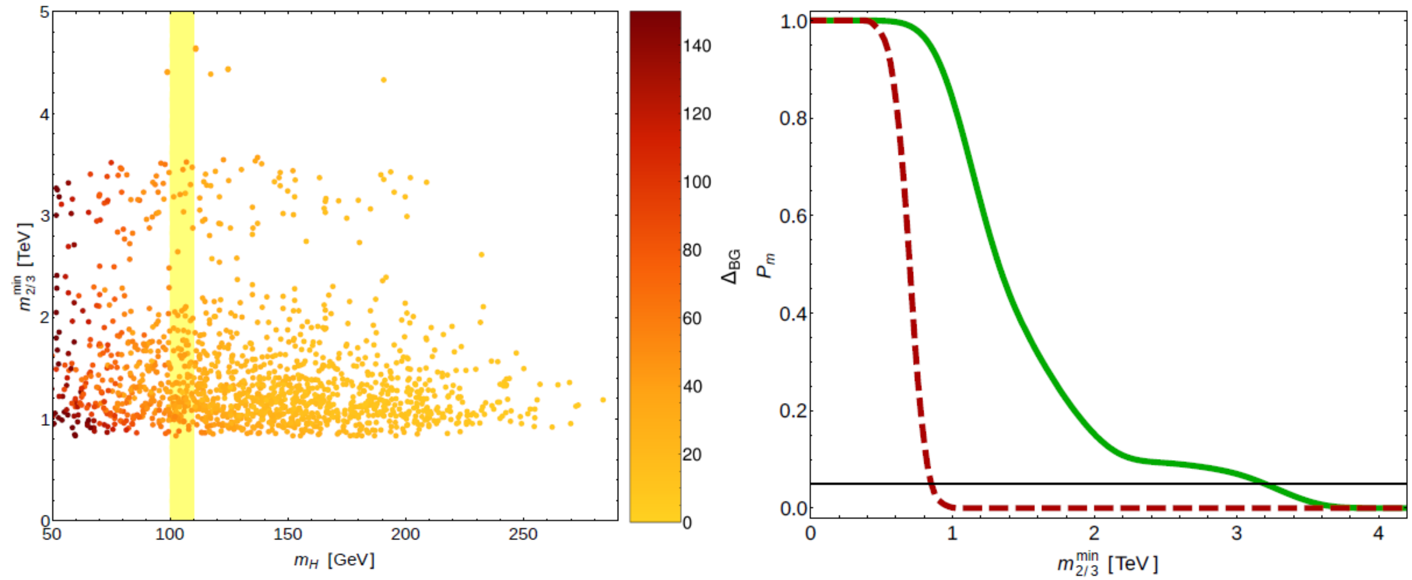
model	$L = 600\ \text{fb}^{-1}$	$L = 3000\ \text{fb}^{-1}$
c_6-only	$c_6 \in (-0.5, 0.8)$	$c_6 \in (-0.4, 0.4)$
full	$c_6 \gtrsim -1.3$	$c_6 \in (-1.2, 2.4)$

The stakes: gauge hierarchy resolution

Carmona

$\mathrm{mMCHM}_{5-1}^{\mathrm{III}>}$

Leptons can even be the main source of the Higgs mass, allowing for the most minimal quark model $q_L \sim \mathbf{5}_{-2/3}, t_R \sim \mathbf{1}_{-2/3}$



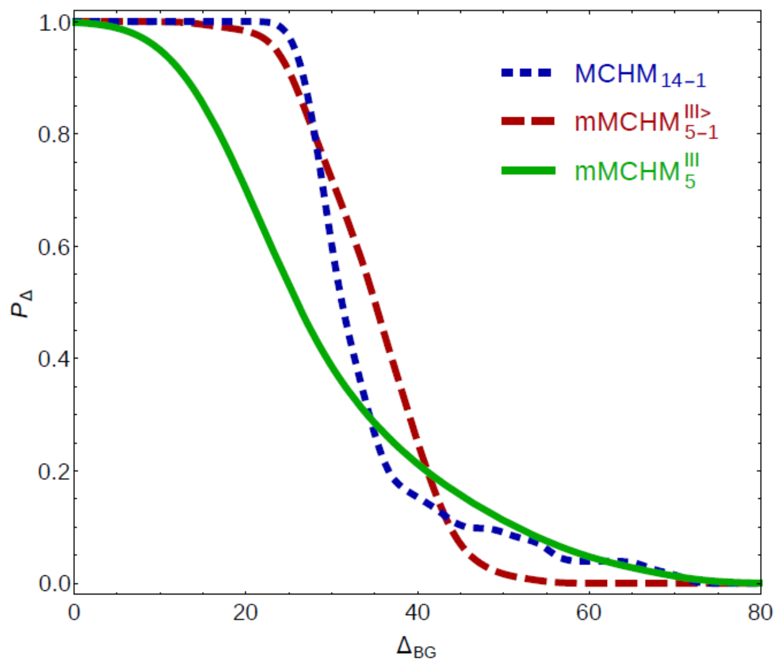
$$Y_*^l = 0.7, \quad Y_*^q = 0.7, \quad f_\pi = 0.8 \text{ TeV}, \quad g_\psi \sim 4.4$$

Adrián Carmona Bermúdez — Flavor, Minimality and Naturalness in Composite Higgs Models — ERC Workshop, Mainz
Slide 17/30

The stakes: gauge hierarchy resolution

Carmona

Comparison of Tuning



- $\text{mMHCM}_5^{\text{III}}$ allows to reconcile minimal tuning with absence of ultra-light partners
- $\text{mMCHM}_{5-1}^{\text{III}>}$ features least dof of all $SO(5)/SO(4)$ models

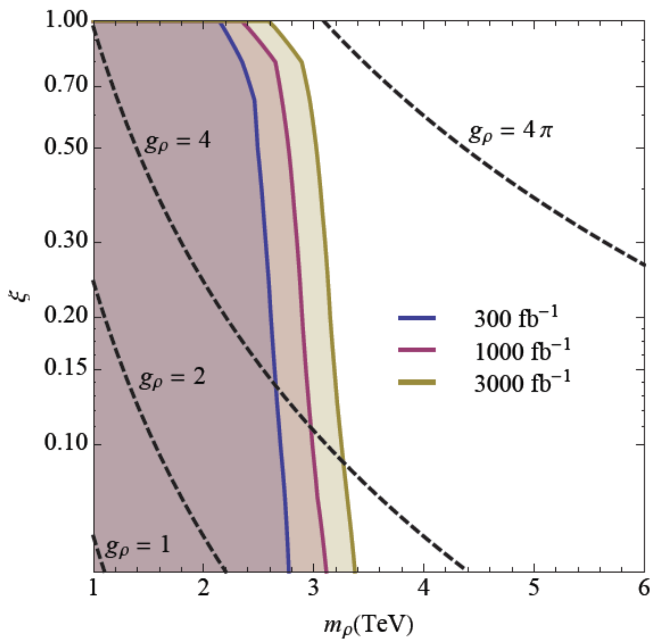
$$Y_*^q = 0.7, \quad f_\pi = 0.8 \text{ TeV}, \quad g_\psi \sim 4.4, \quad m_{2/3}^{\text{min}} > 1 \text{ TeV}$$

The stakes: GH resolution, many new states to discover

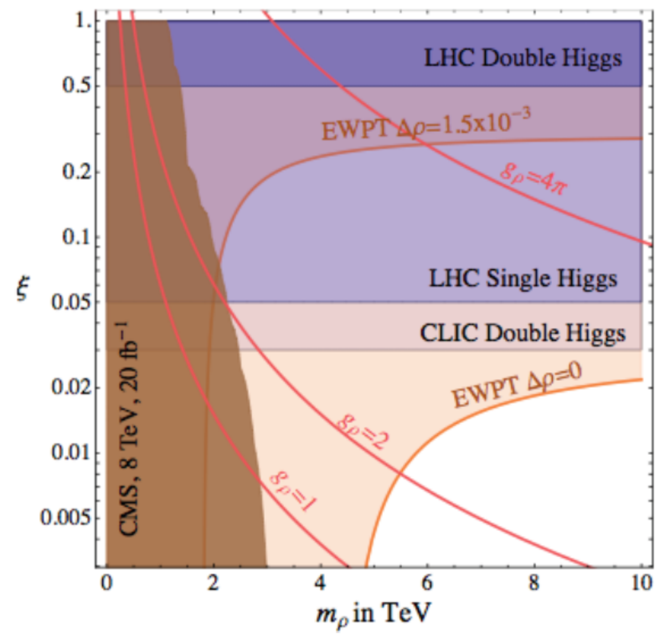
Searching for $\rho \to Vh$

Kaminska

here assumed $m_\rho = g_\rho f = g_\rho v_{EW}/\sqrt{\xi}$



M.Hoffmann, AK, R.Nikolaidou, S.Paganis



Contino, Grojean, Pappadopulo, Rattazzi, Thamm

The stakes: GH resolution, many new states to discover

Impact of composite fermions

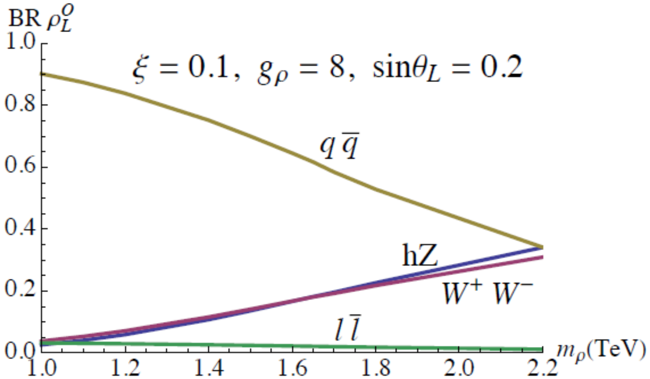
Kaminska

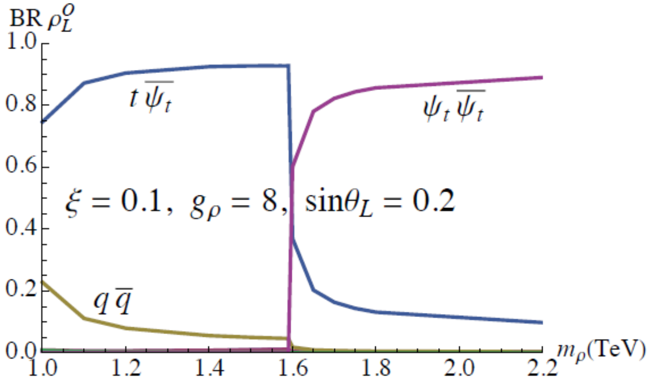
spin-1 resonances may couple directly to fermion resonances

$$-i\bar{\psi} g_\rho \gamma^\mu T^a \rho_\mu^a \psi$$

partial compositeness $\rightarrow$ mass mixing with SM fermions $\rightarrow$ modified BR of spin-1 resonances

- 3 gen. resonances only,
  $m_T \gtrsim 2\,\mathrm{TeV}$ (left) and $m_T \sim 0.8\,\mathrm{TeV}$ (right)



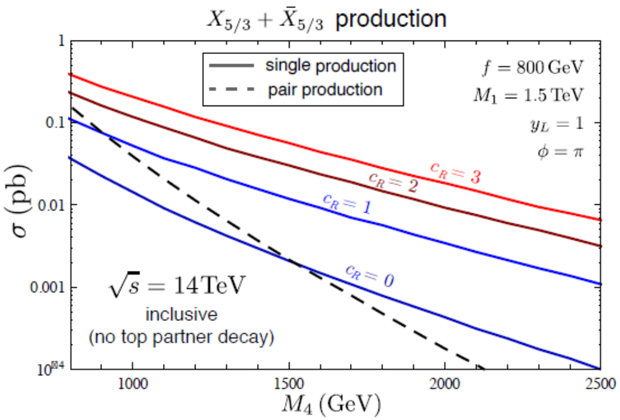


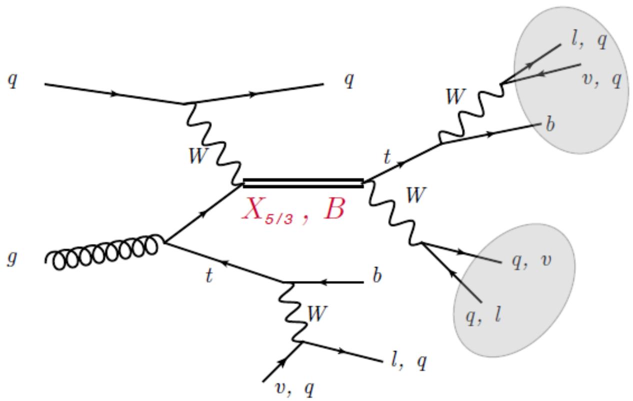
The stakes: GH resolution, many new states, new tool of boosted techniques

Prospects for composite quark partners at LHC run II

Search for top partners in the $q\bar{t}tW$ final state with semi-leptonic decay of tW.

Flacke



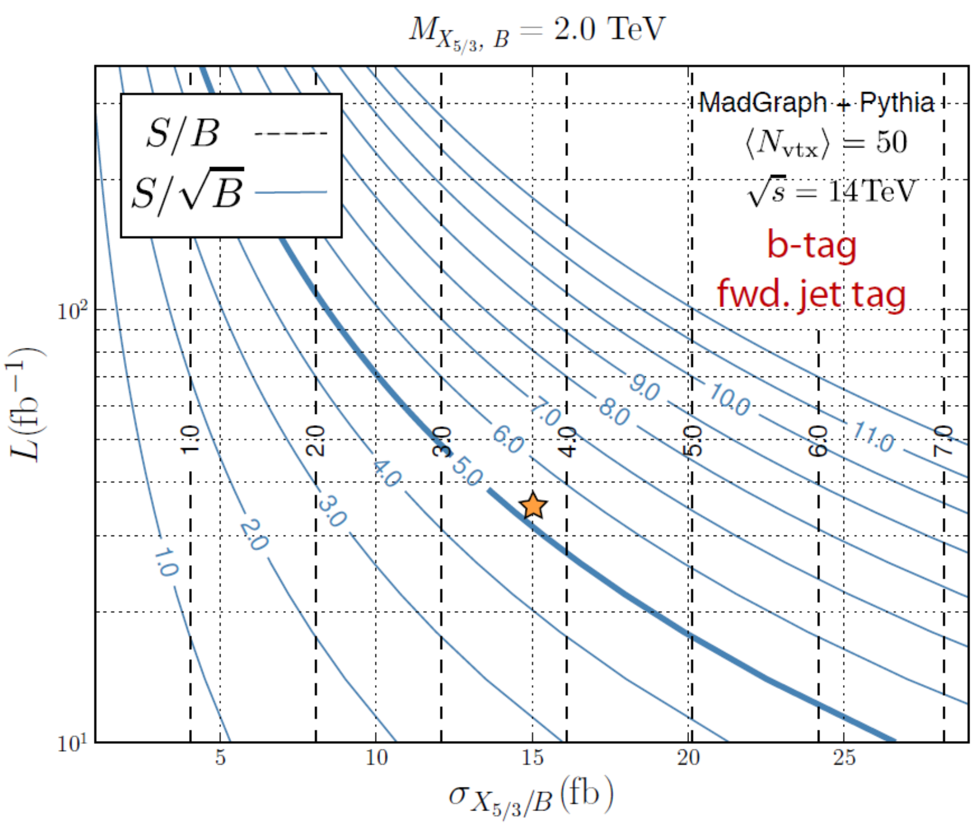


The final state is characterized by		We use this by
- a high energy forward jet	$\rightarrow$	used as a tag
- two b's	$\Rightarrow$	demand two b-tags
- a highly boosted tW system with:		
– one hard lepton,	$\rightarrow$	$p_T^l > 100\,\text{GeV}$ cut
– missing energy,		
– "fat jets",	$\rightarrow$	reconstruct boosted t/W using Template Overlap Method (TOM)

The stakes: GH resolution, many new states, new tool of boosted techniques

Prospects for composite quark partners at LHC run II

Flacke



M. Backović, TF, S. J. Lee, G. Perez [arXiv: 1409.0409]

Also need SM in the boosted regime

QCD corrections in boosted top production

Consider very large pair invariant mass where $\tau = M_{t\bar{t}}^2/s \to 1$

Pecjak

$$\frac{d\sigma}{dM_{t\bar{t}}}(s, m_t, M_{t\bar{t}}) = \sum_{i,j} \int_\tau^1 \frac{dz}{z}\, ff_{ij}(\tau/z, \mu_f)\, \frac{d\hat{\sigma}_{ij}}{dM_{t\bar{t}}}(z, m_t, M_{t\bar{t}}, \mu_f)$$

$$ff_{ij}(y, \mu_f) = \int_y^1 \frac{dx}{x}\, f_{i/h_1}(x, \mu_f)\, f_{j/h_2}(y/x, \mu_f)$$

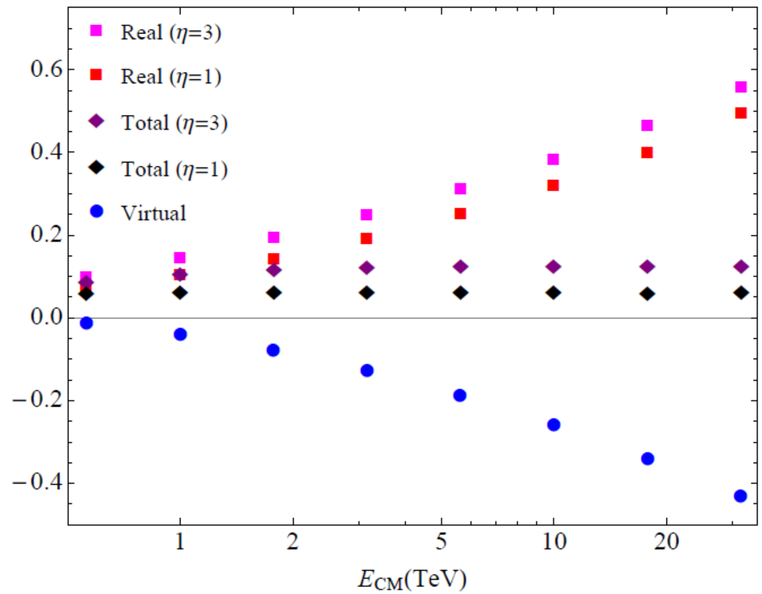
Two kinds of large logarithms appear:

- soft logs: $[\ln(1-z)/(1-z)]_+ \quad (z \equiv M_{t\bar{t}}^2/\hat{s})$
- small-mass (collinear) logs: $\ln m_t/M_{t\bar{t}}$

Goal: set up a framework which can factorize cross sections and resum both types of logs, i.e. understand factorization in double soft and small-mass limit

SM also entering unbroken SU(2) regime

Results for Massless Quarks



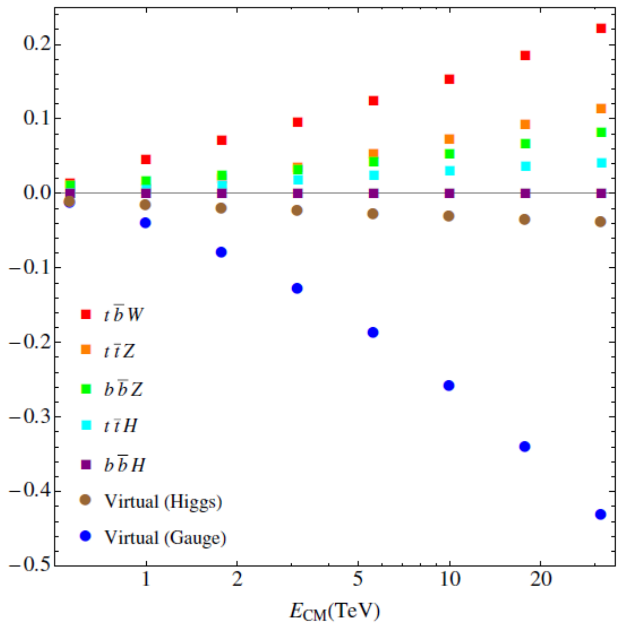
Turczyk

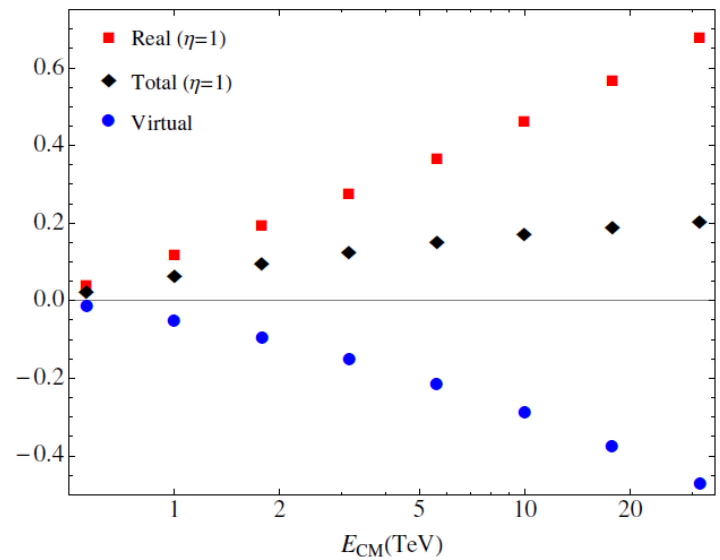
- Tree level: $gg \to u\bar{u}$ and $gg \to d\bar{d}$
- Real radiation: $gg \to u\bar{u}Z$, $gg \to d\bar{d}Z$, $gg \to u\bar{d}W^-$ and $gg \to d\bar{u}W^+$
- $SU(2)$: $\sigma(u\bar{u}) = \sigma(d\bar{d})$, $\sigma(u\bar{d}W^-) = \sigma(d\bar{u}W^+) = 2\sigma(u\bar{u}Z) = 2\sigma(d\bar{d}Z)$
- Cancellation $3\sigma(u\bar{d}W) + 2v_W\sigma(u\bar{u}) \to 0$
- No full cancellation for experimental observables!

SM also entering unbroken SU(2) regime

Numerical Results for Physical Top Quark Case

Turczyk





- Same as before, Yukawa coupling for bottom much smaller
- Used $t tag for MadGraph5_aMC@NLO

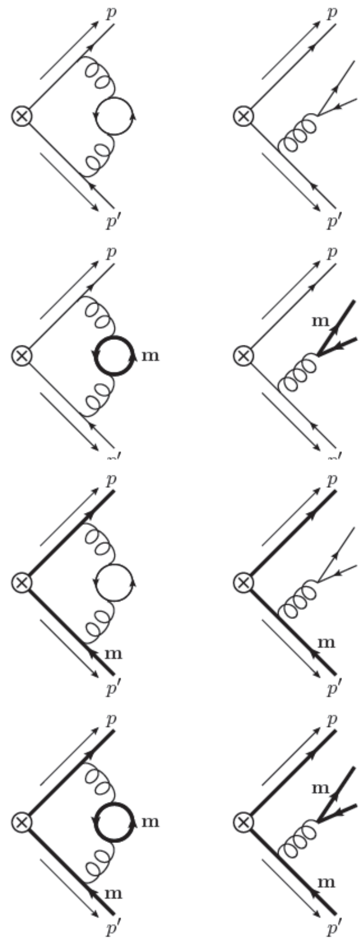
$\Rightarrow$ Excludes a region of width $15\Gamma_t$ around the on-shell t-quark

- No full cancellation for experimental observables!

NP searches enabled only by precise jet physics calculations

Hoang

Fully Massive Thrust



→ fully massless

- Full N³LL' (u.t. 4-loop cusp)+ 3-loop non-singular
- Gap scheme for soft function

Only SCET authors: Becher, Schwartz, Fleming, AH, Mantry, Stewart Bauer, Fleming, Lee, Sterman

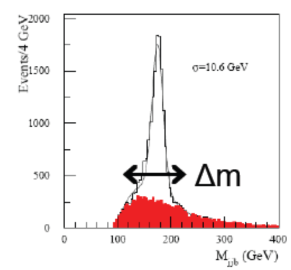
→ secondary massive

- Full N²LL'/N³LL

→ New: In detail in this talk.

→ primary massive

- bHQET: full N²LL'/N³LL
  → valid for: $\Delta m_{jet} << m$
- NLL'/N²LL for other cases



→ primary massive secondary massive

New: complete and systematic description

→ Only briefly in this talk.

SM: magic still possible

Magic Connection To The Bare $q\bar{q}$ Soft Function

Surprisingly, we find that one can produce the bare $q\bar{q}$ soft function for all non-trivial color structures to all orders in ϵ by making simple replacements!

For example, if we take $\ln^n(x) \to 0$ for all $n > 1$ and $\ln(x) \to \frac{1}{2\epsilon}$ in $S^{t\bar{t}}_{\text{bare}}(x \to 0, \lambda, \mu)\Big|_{C_F n_f T_F}$, we reproduce

Belitsky, Phys. Lett. B442, 307 (1998)

Schabinger

$$S^{q\bar{q}}_{\text{bare}}(\lambda, \mu)\Big|_{C_F n_f T_F} = \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\mu^{4\epsilon}}{\lambda^{1+4\epsilon}} \left[\frac{16}{3\epsilon^2} + \frac{80}{9\epsilon} + \frac{448}{27} - \frac{56\pi^2}{9} + \epsilon\left(\frac{2624}{81} - \frac{280\pi^2}{27} - \frac{992\zeta(3)}{9}\right) + \mathcal{O}\left(\epsilon^2\right)\right]$$

We conjecture that, for all non-trivial color structures, we can obtain the massless result via $\ln^n(x) \to 0$ for all $n > 1$ and $\ln(x) \to \frac{1}{L\epsilon}$ at L loop order by expanding to one order higher in ϵ than normal.

SM: puzzles still remain

Holomorphy

Manohar

	$(X^+)^3$	$(X^+)^2H^2$	ψ^2X^+H	$(\bar{L}R)(\bar{L}R)$	$(\bar{L}R)(\bar{R}L)$	JJ	ψ^2H^3	H^6	H^4D^2	ψ^2H^2D
$(X^+)^3$	$\mathfrak{h}$	$\to 0$	0	0	0	0	0	0	0	0
$(X^+)^2H^2$	$\mathfrak{h}$	$\mathfrak{h}$	$\mathfrak{h}$	0	0	$\nexists$	0	0	$\to 0$	$\to 0$
ψ^2X^+H	$\mathfrak{h}$	$\mathfrak{h}$	$\mathfrak{h}$	$\mathfrak{h}_F$	$\to 0$	$\to 0$	$\to 0$	0	$\nexists$	$\to 0$
$(\bar{L}R)(\bar{L}R)$	$\to 0$	$\nexists$	$\mathfrak{h}_F$	$\mathfrak{h}_F$	$Y_u^\dagger Y_{e,d}^\dagger$	$Y_u^\dagger Y_{e,d}^\dagger$	$\nexists$	$\nexists$	$\nexists$	$\to 0$
$(\bar{L}R)(\bar{R}L)$	$\to 0$	$\nexists$	$\to 0$	$Y_u Y_d,\ Y_u^\dagger Y_e^\dagger$	$\mathfrak{h}_F$	$*$	$\nexists$	$\nexists$	$\nexists$	$\to 0$
JJ	$\to 0$	$\nexists$	$\to 0$	$Y_u Y_{e,d}$	$*$	$*$	$\nexists$	$\nexists$	$\nexists$	$*$
ψ^2H^3	$\to 0$	$Y_{u,d,e}^\dagger$	$\mathfrak{h}$	$\mathfrak{h}$	$*$	$*$	$*$	$\nexists$	$*$	$*$
H^6	$\to 0$	$*$	$\nexists$	$\nexists$	$\nexists$	$\nexists$	$*$	$*$	$*$	$*$
H^4D^2	$\to 0$	$\to 0$	$\to 0$	$\nexists$	$\nexists$	$\nexists$	$\to 0$	$\nexists$	$*$	$*$
ψ^2H^2D	$\to 0$	$\to 0$	$\to 0$	$\to 0$	$\to 0$	$*$	$\to 0$	$\nexists$	$*$	$*$

Next chapter of our story

- Struggle between the SM and the data continues
- More data will come in LHC Run 2, HL-LHC, Belle 2, LBNF, Muon g-2, Mu2e, Xenon 1T, IceCube, Fermi-LAT, Planck, BICEP-II, ILC, FCC/CEPC/SPPC, LSST, DESI, …

Next chapter of our story

"May you live in interesting times"

- The questions are huge

Next chapter of our story

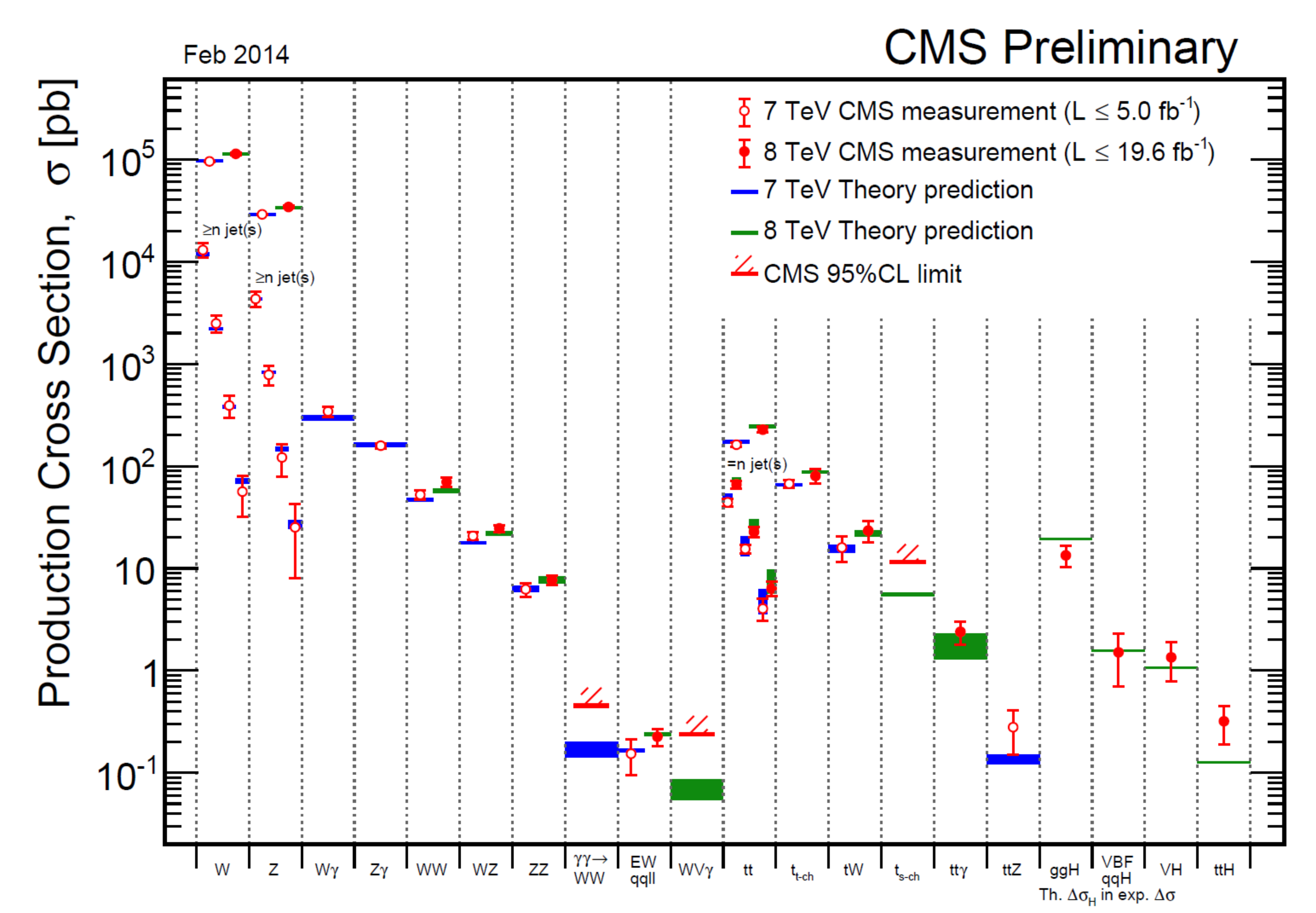
"May you live in interesting times"

- The questions are huge
- The questions are patient

Next chapter of our story

"May you live in interesting times"

- The questions are huge
- The questions are patient
- The questions are very patient



ATLAS https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

Also CMS https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined