Lessons from the LHC and future prospects

Physics Department,

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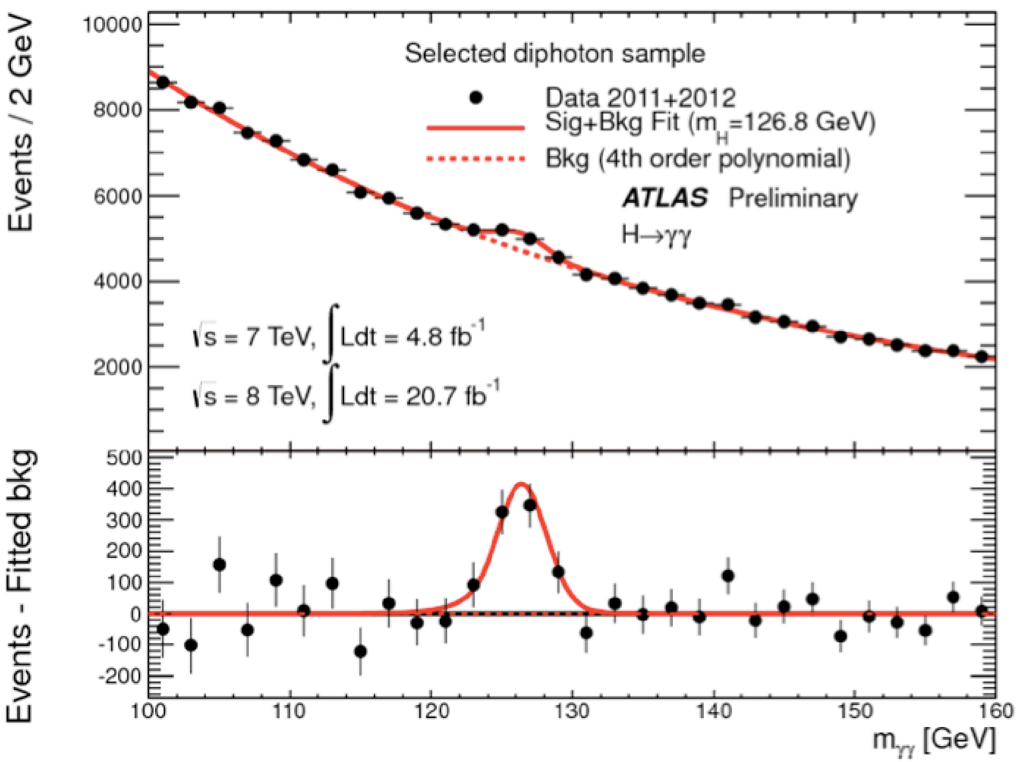
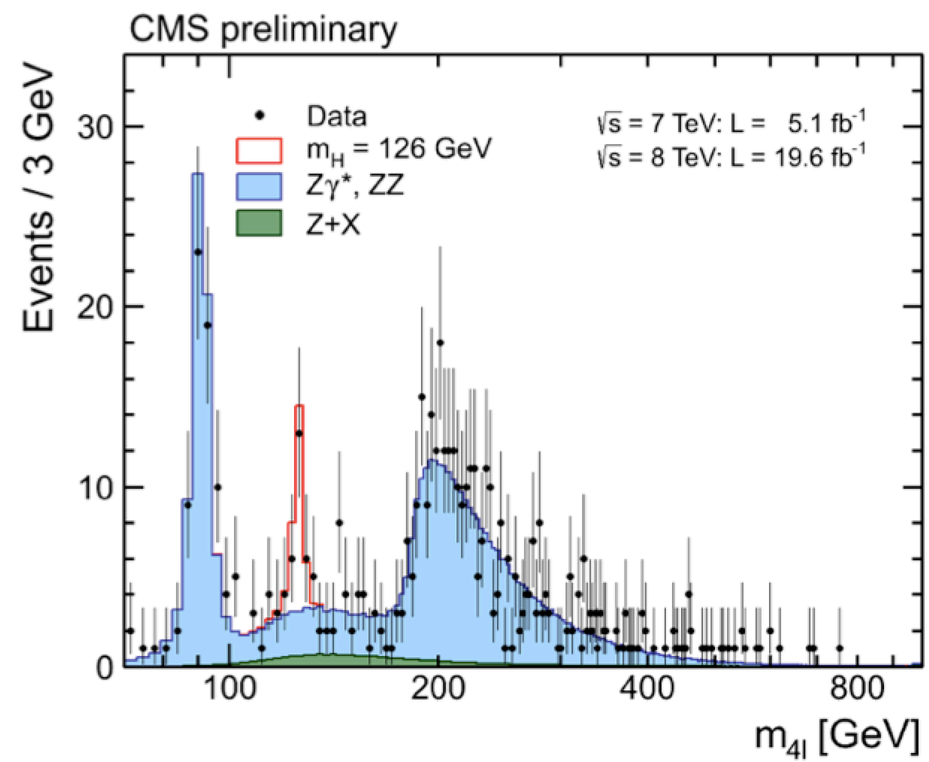
Key outcomes of 3 yrs at the LHC: 1

+ The Higgs signal has been detected through sharp mass peaks in several channels

+ Its production and decay rates are consistent with the SM expectation, at the +/– 20% level .....

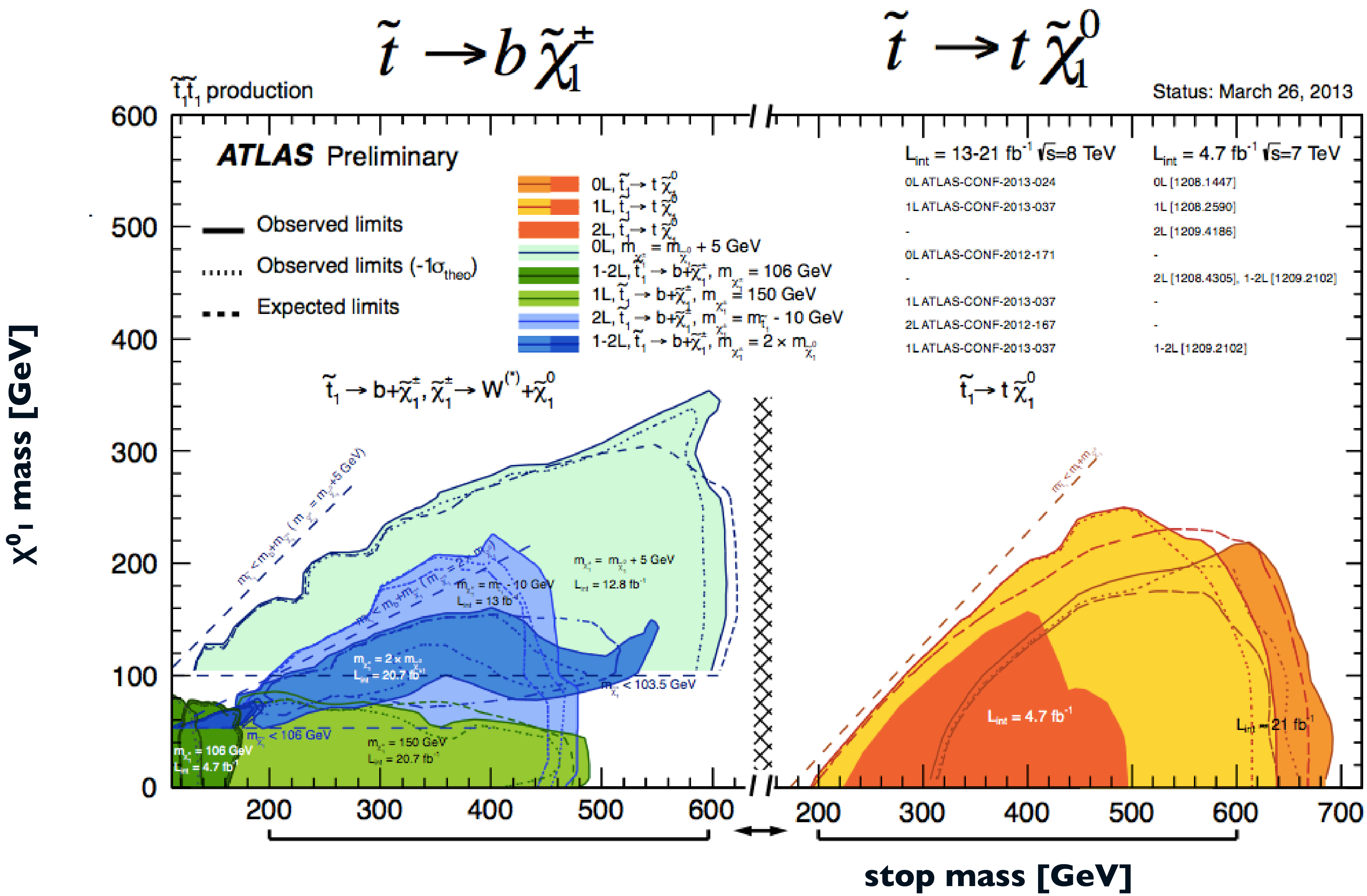




.... how far can we push the accuracy of these tests, and probe the mechanism of EWSB ?

Key outcomes of 3 yrs at the LHC: 2

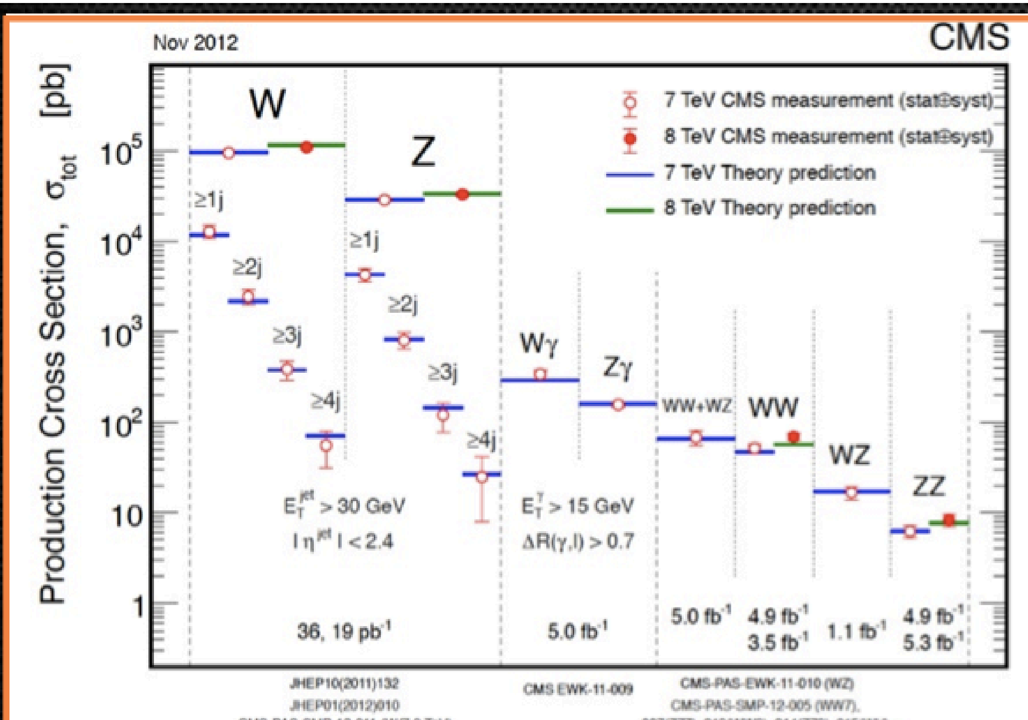
No strong sign of BSM, in all places the experiments have looked .....

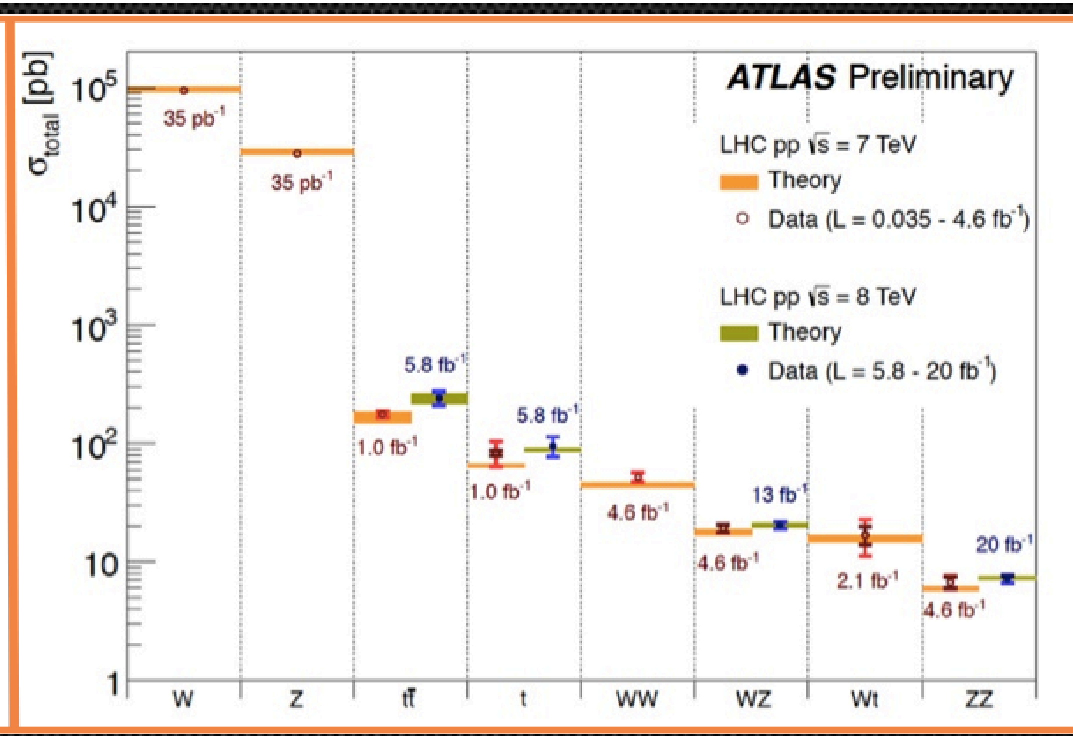


.... how to access regions of parameters of BSM models where the sensitivity is low?

Key outcomes of 3 yrs at the LHC: 3

The theoretical description of high-Q^2 processes at the LHC is very good ....





.... but must and can be improved

Tasks for the future LHC programme

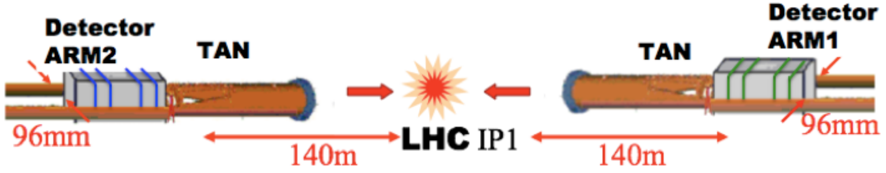
- Continue the search for BSM phenomena
- Continue improving the accuracy of Higgs measurements
- Continue the exploration of SM phenomena, improving the accuracy of theoretical calculations and of experimental measurements
  - => increase the potential for precise measurements of the Higgs and for more sensitive BSM searches

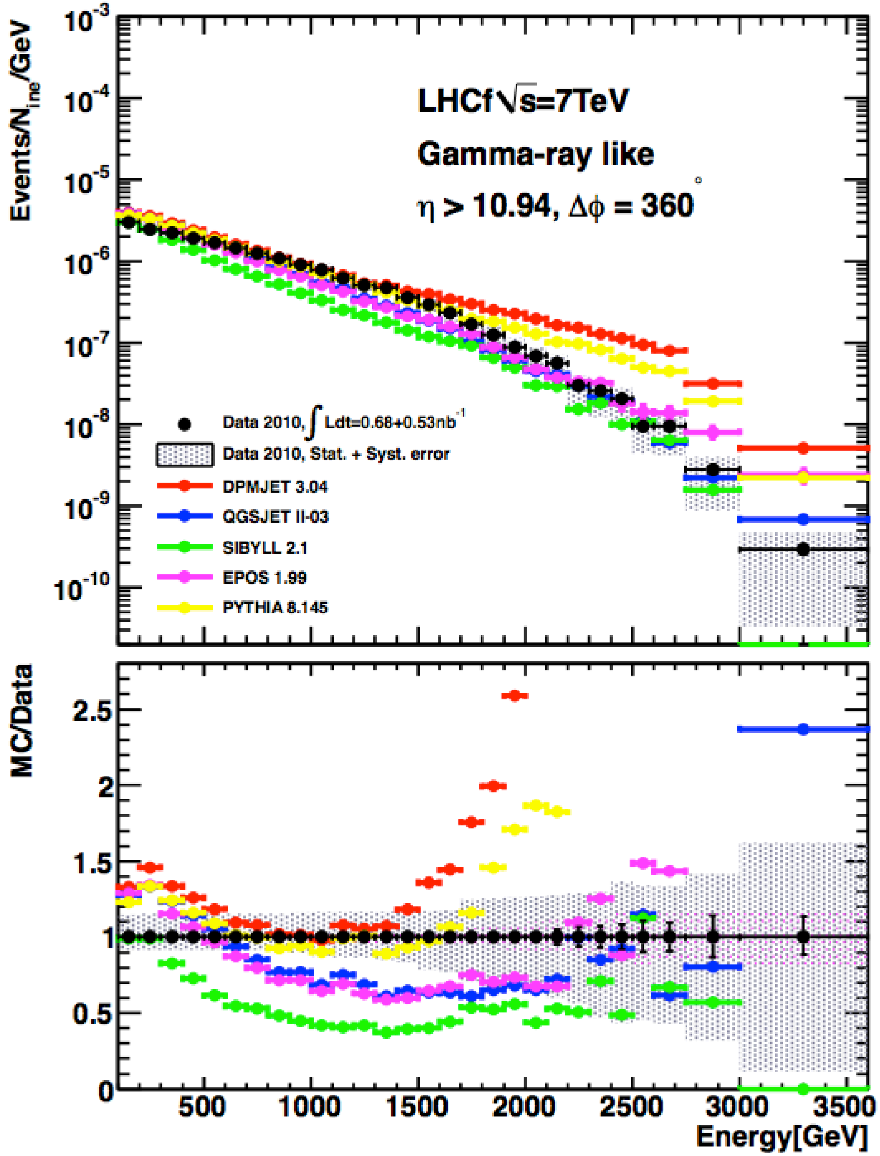
Outline of this talk

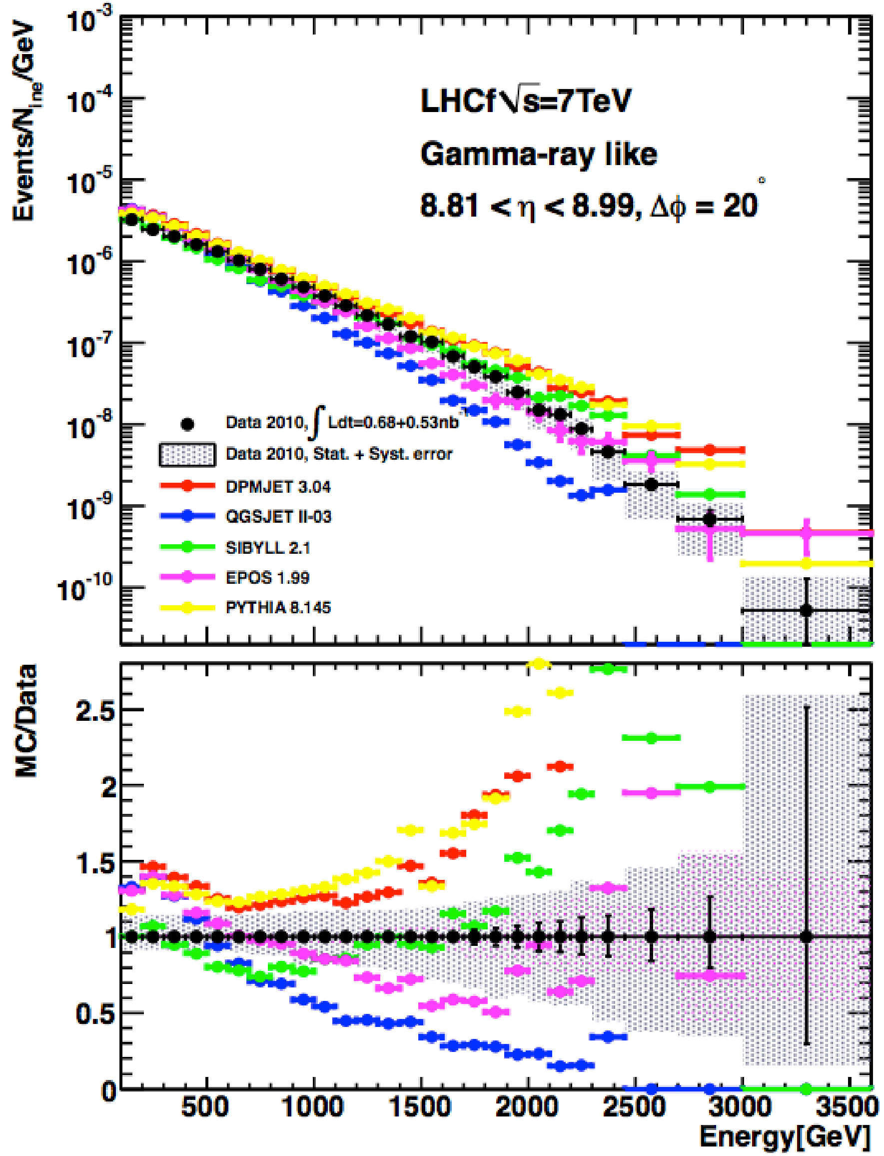
- Review some of the achievements of the LHC, focusing on lesser known aspects of the programme
- Review the case for BSM physics at the LHC
- Discuss the role and prospects of precision physics at the LHC
- Present the long-term plans for the LHC, and for possible future high-energy pp colliders

LHCf: Very forward energy flow

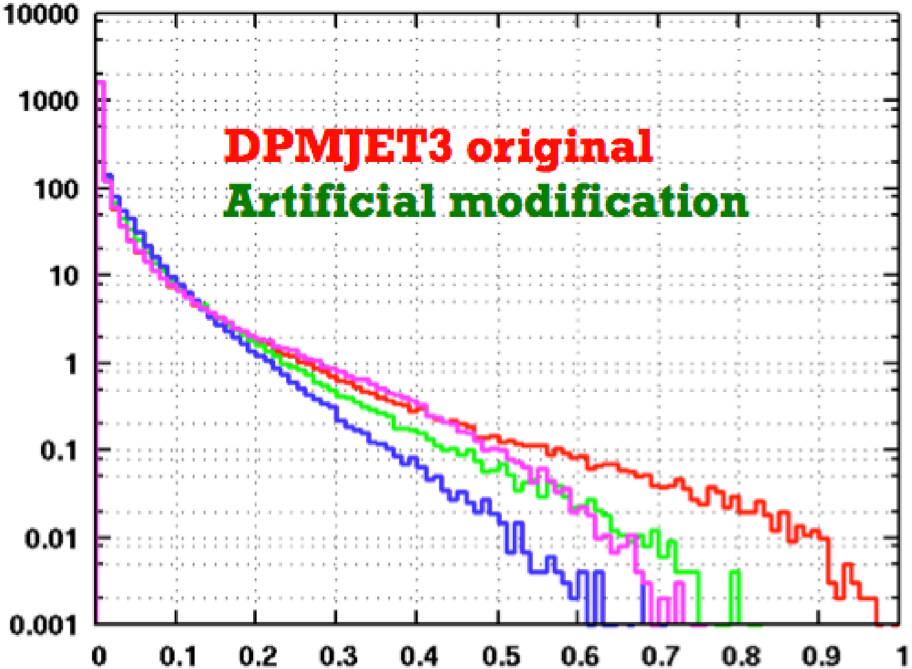
"Measurement of zero degree single photon energy spectra for √s = 7 TeV proton-proton collisions at LHC"
PLB 703 (2011) 128



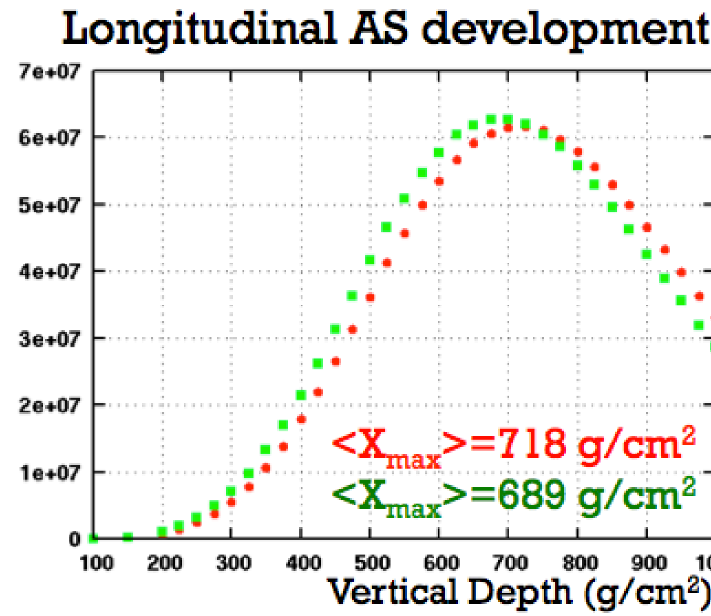


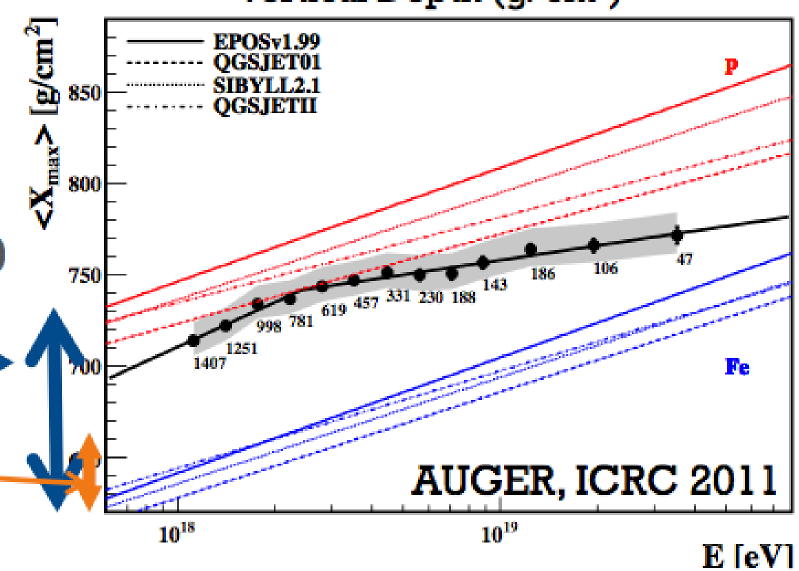


π^0 spectrum and air shower



π^0 spectrum at $E_{lab} = 10^{17}$eV





- ✓ Artificial modification of meson spectra (in agreement with differences between models)
- ✓ $\Delta\langle X_{max}(p\text{-}Fe)\rangle \sim$ 100 g/cm^2
- ✓ Effect to air shower ~ 30 g/cm^2

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

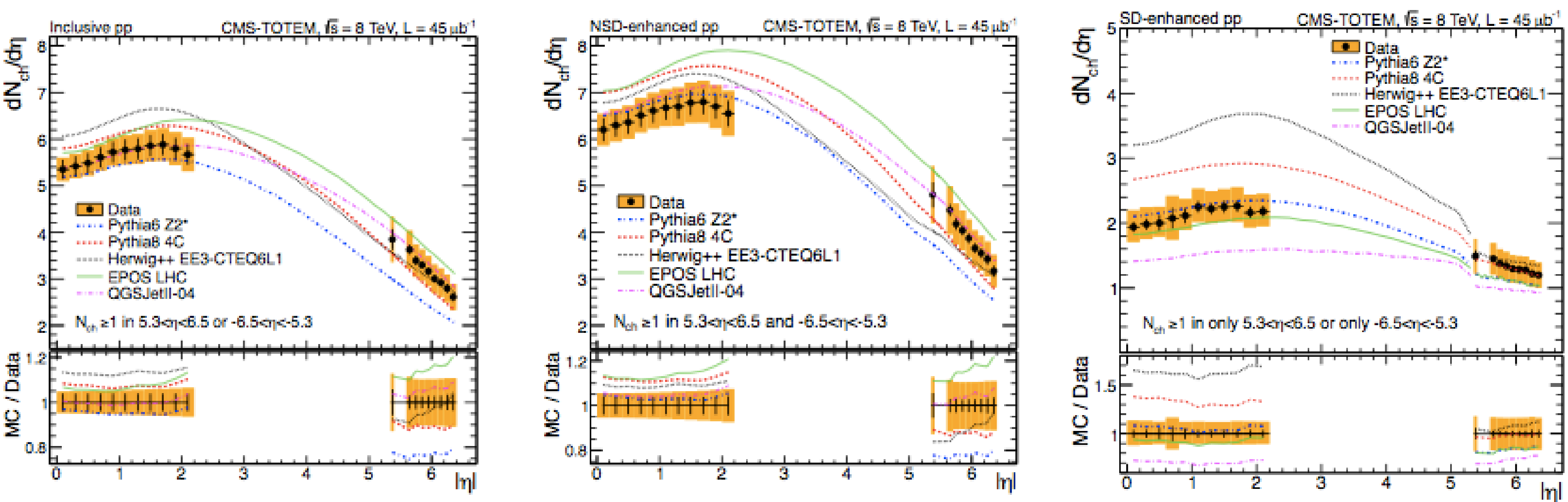
CERN-PH-EP/2014-063
2014/05/12

CMS-FSQ-12-026
CERN-PH-EP-TOTEM-2014-002

Measurement of pseudorapidity distributions of charged particles in proton-proton collisions at $\sqrt{s} = 8$ TeV by the CMS and TOTEM experiments

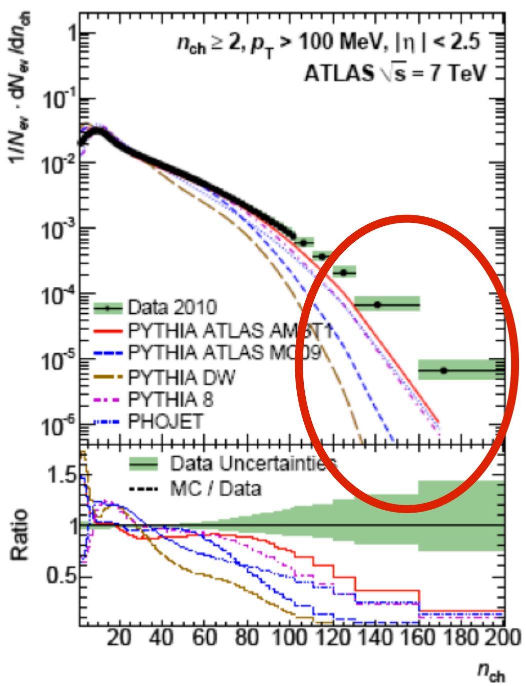
The CMS and TOTEM Collaborations*

http://arxiv.org/abs/1405.0722

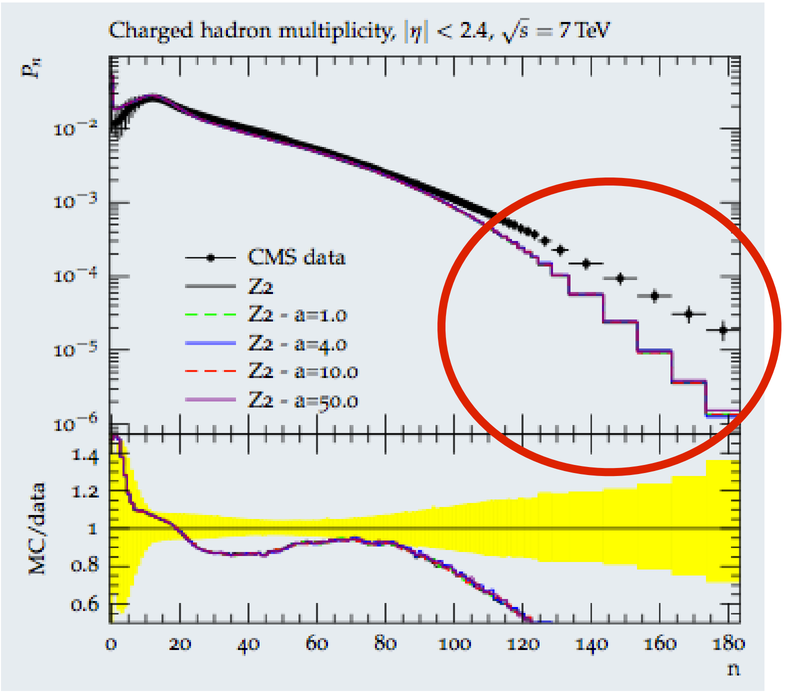


Properties of final states in "0-bias" events

Large multiplicity final states



ATLAS, http://arxiv.org/pdf/1012.5104v2



S.Alderweireldt, MPI-2011

Need a detailed characterization of the structure of large-multiplicity final states:

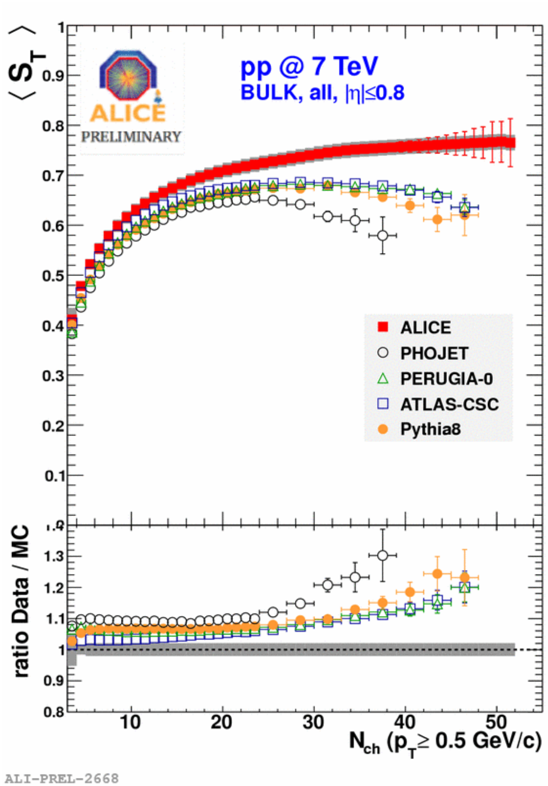
- **are they dominated by 2-jets back to back?**
- **are they dominated by many soft jets (e.g. multiple semi-hard collisions)**
- **do they look "fireball"-like (spherically symmetric)?**
- **does the track-pt spectrum of high-Nch events agree with MCs?**
- **y-distribution of very soft tracks in high-Nch events?**
- **.....**

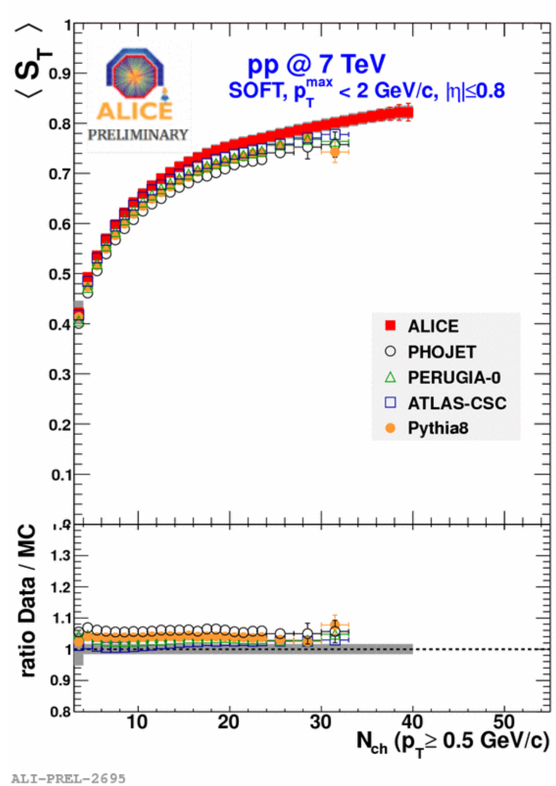
Are we staring at something *fundamental*, or is this just QCD chemistry and MC-tuning?

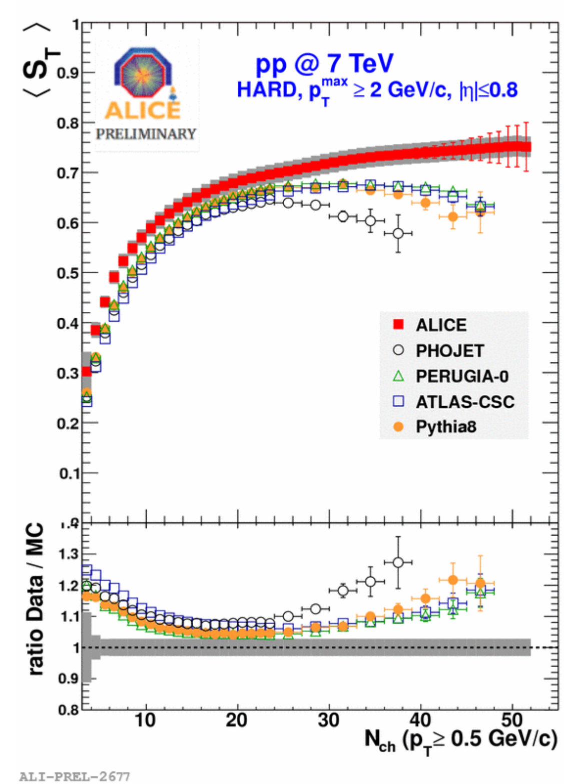
.... see also the CMS ridge effect

Further insight and puzzles on large-N_{ch} events

ALICE study of transverse sphericity vs N_{ch} arXiv:1110.2278







Events are generically more spherical, less jetty, than MC.

Most of the discrepancy comes however from hard events, not soft ones

Given the smaller rapidity coverage of ALICE, the multiplicities used in this study, with N_{ch} up to ~50, probe final state consistent with those of extreme N_{ch} (>100) measured by ATLAS/CMS in a larger rapidity volume

Open challenge:

To prove that the underlying mechanisms of multiparticle production at high energy are *understood*, in addition to being simply *properly modeled*

$B_s \to \mu^+\mu^-$

(LHCb+CMS) : B(Bs →μ+μ–) = (2.9±0.7) x 10^{-9}

Instrinsic TH uncertainty **below 1%**, after recent calculation of 3-loop NNLO QCD and 2-loop NLO EW effects:

arXiv:1311.0903v2

FLAVOUR(267104)-ERC-53, LTH 990,
SFB/CPP-13-82, TTP13-033

$B_{s,d} \to \ell^+\ell^-$ in the Standard Model

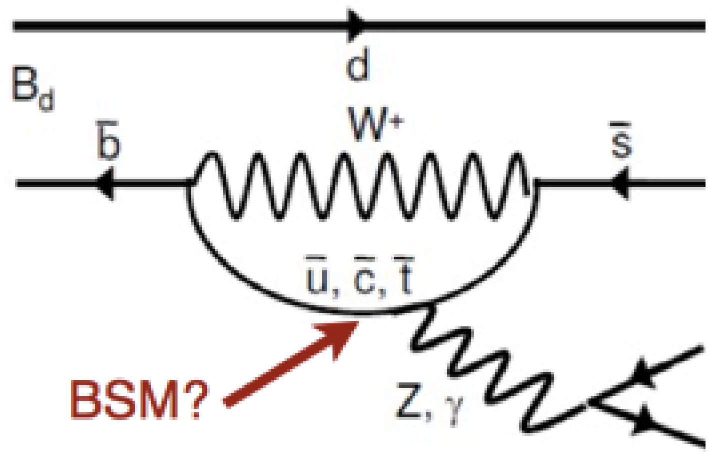
Christoph Bobeth,[1] Martin Gorbahn,[2,1] Thomas Hermann,[3]
Mikołaj Misiak,[4,5] Emmanuel Stamou,[1,6] and Matthias Steinhauser[3]

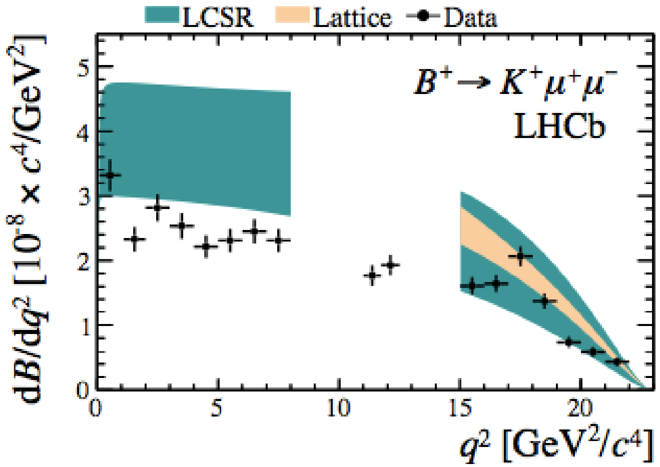
Uncertainty dominated by f_{Bs} (lattice)

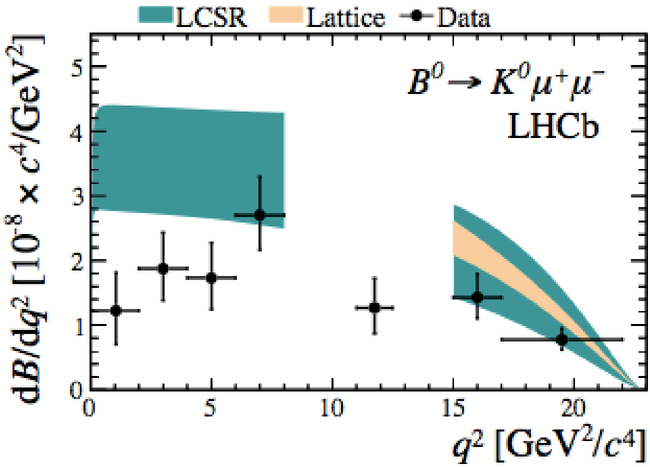
⇒ November 2013:

(Theory) : B(Bs →μ+μ–) = (3.65 ± 0.23) x 10^{-9}

Interesting anomalies are emerging from B decays





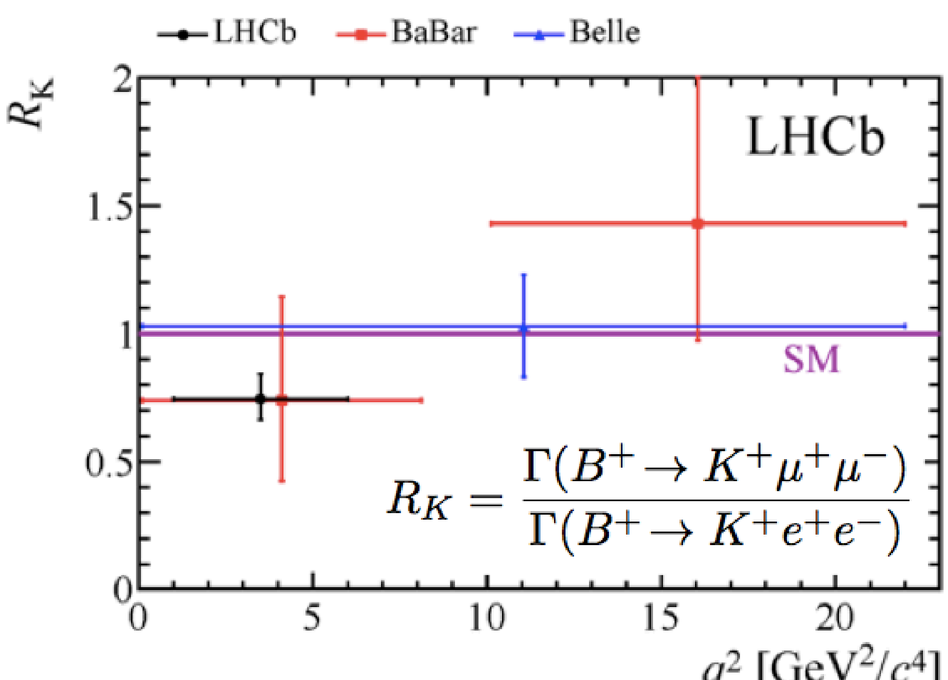


LHCb-PAPER-2014-006 updated to 3/fb

Decay mode	Measurement	Prediction
$B^+ \to K^+\mu^+\mu^-$	$8.5 \pm 0.3 \pm 0.4$	10.7 ± 1.2
$B^0 \to K^0\mu^+\mu^-$	$6.7 \pm 1.1 \pm 0.4$	9.8 ± 1.0
$B^+ \to K^{*+}\mu^+\mu^-$	$15.8\ ^{+3.2}_{-2.9} \pm 1.1$	26.8 ± 3.6

expect update soon

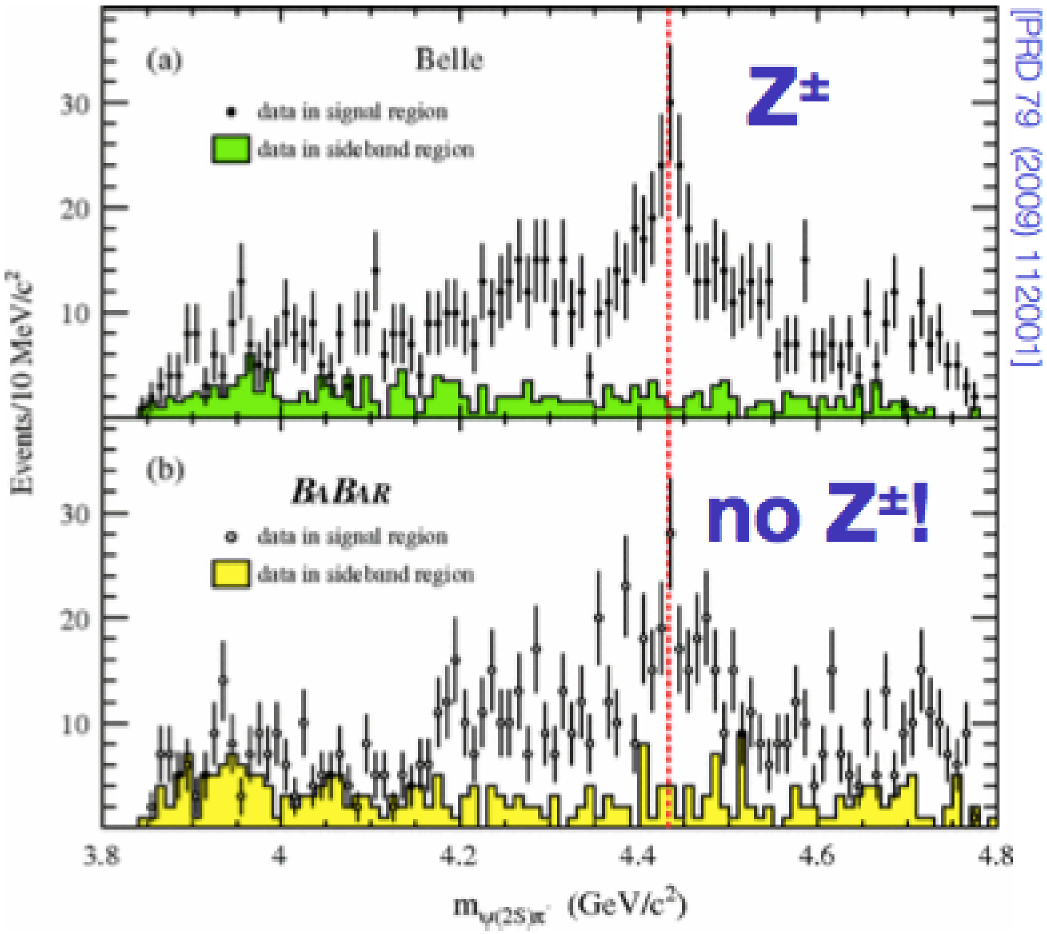
LHCb-PAPER-2014-024 (upcoming)

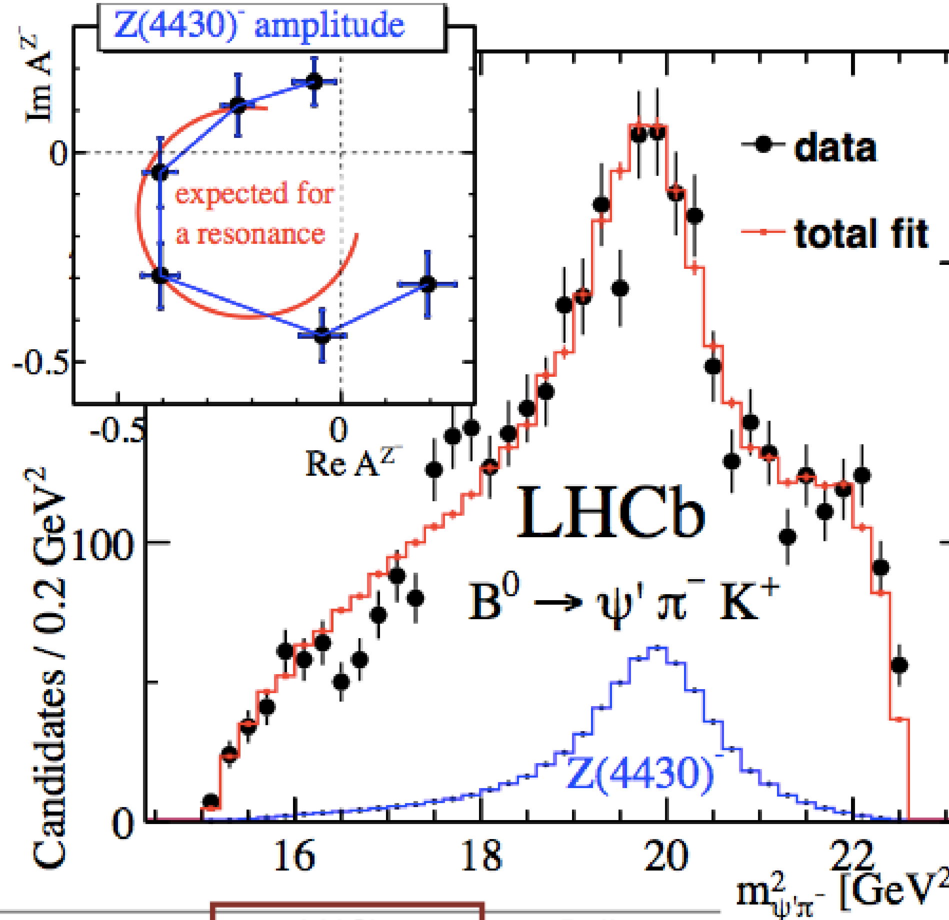


$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{sys})$$

~2.5σ from SM value of 1

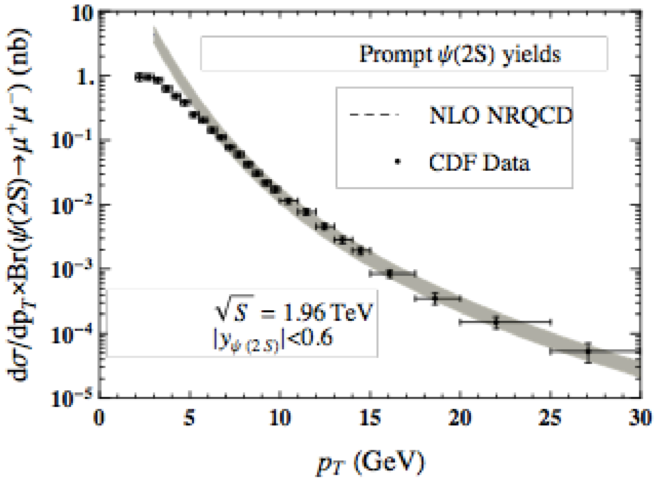
Confirmation of the Z(4430), evidence of 4-quark nature

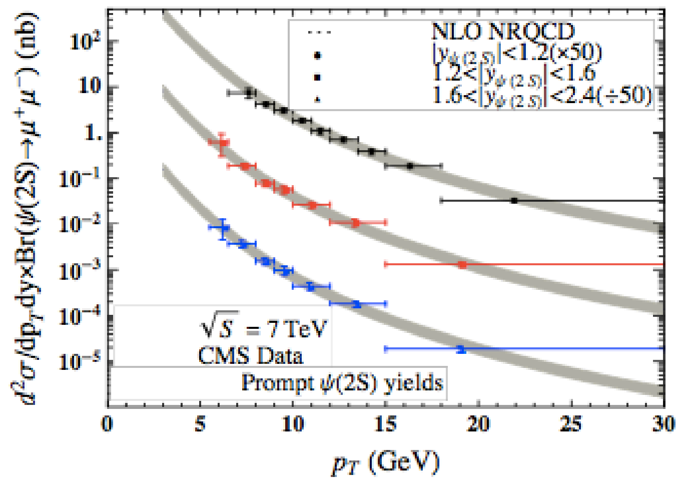




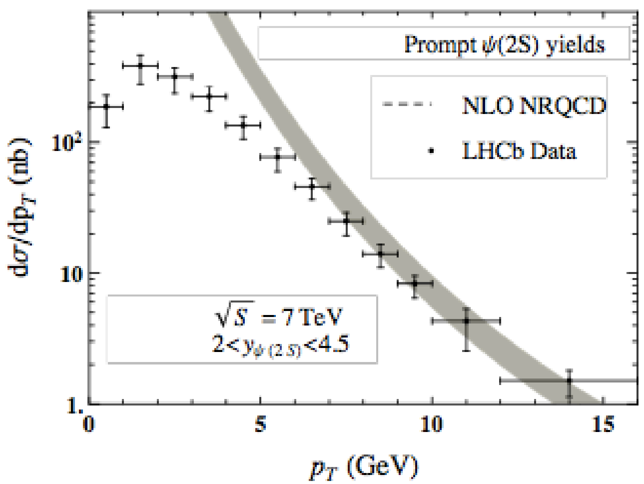
	LHCb	Belle
$M(Z)$ [MeV]	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
$\Gamma(Z)$ [MeV]	$172 \pm 13^{+37}_{-34}$	$200^{+41}_{-46}{}^{+26}_{-35}$
f_Z [%]	$5.9 \pm 0.9^{+1.5}_{-3.3}$	$10.3^{+3.0}_{-3.5}{}^{+4.3}_{-2.3}$
f_Z^I [%] (with interference)	$16.7 \pm 1.6^{+2.6}_{-5.2}$	–
significance	$> 13.9\sigma$	$> 5.2\sigma$
J^P	1^+	1^+
	New (large) systematic included	

The understanding of chamonium polarization at large p_T remains a puzzle !



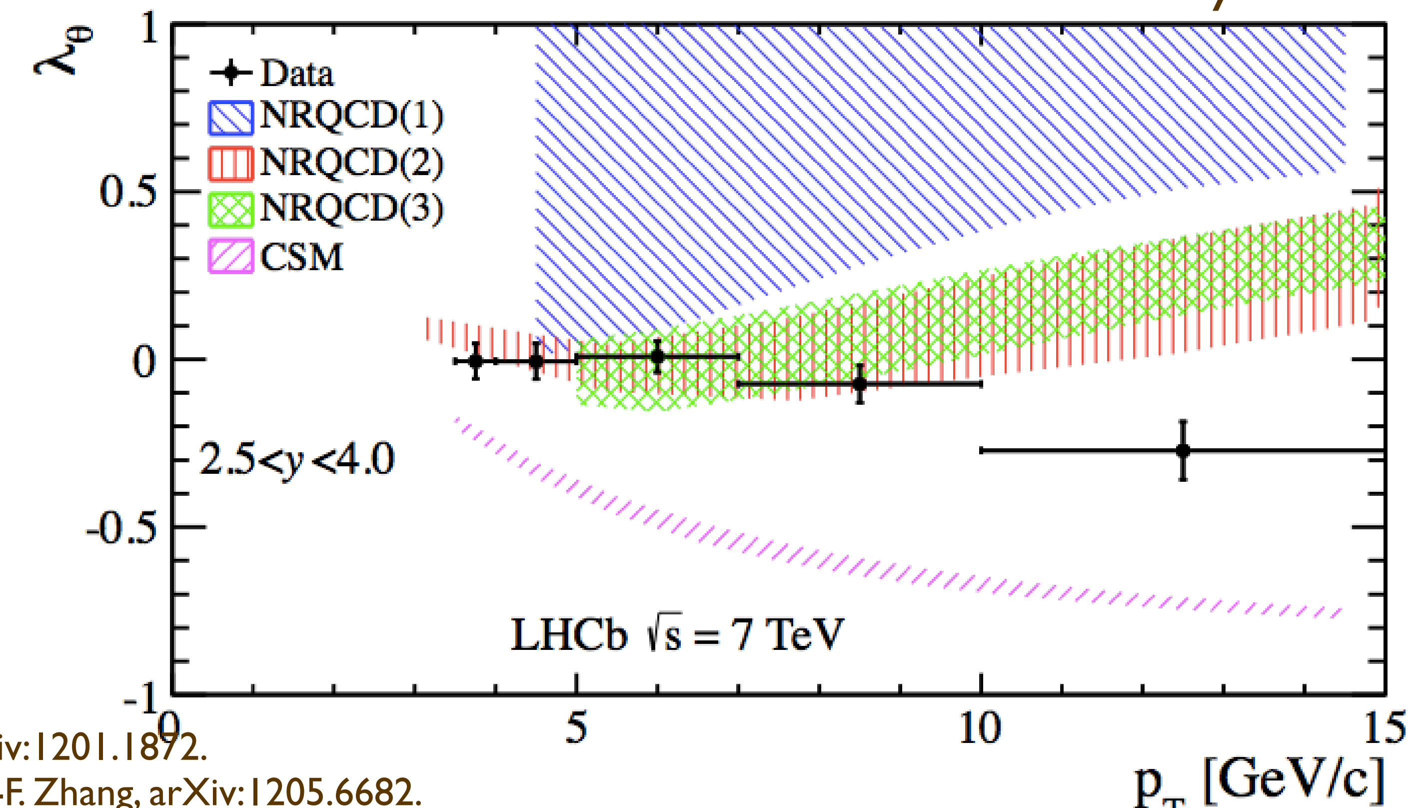


from H-S Shao PhD thesis, PKU

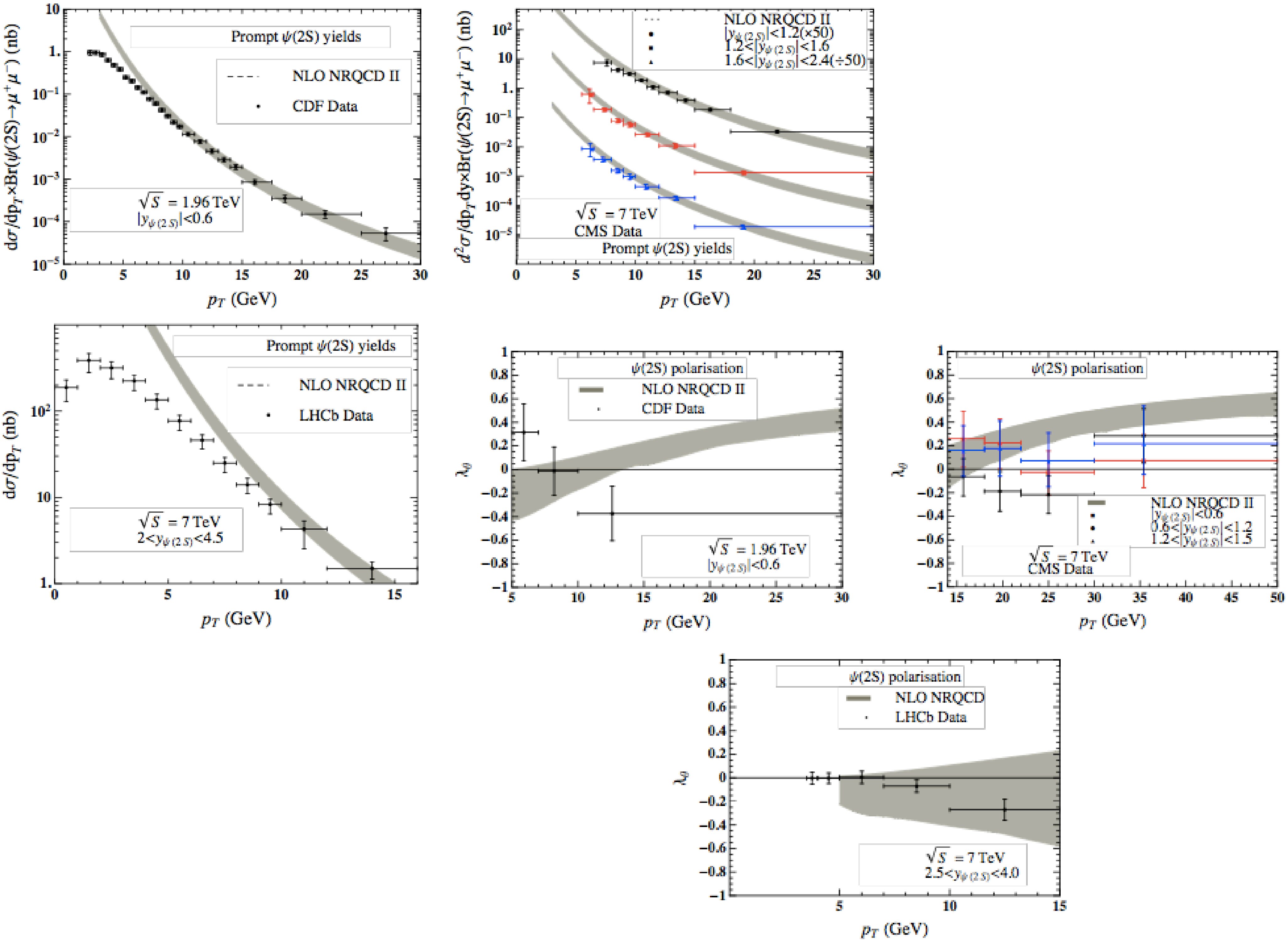


2011 LHCb data: ψ(2S) polarization

in the helicity frame



(1) M. Butenschoen and B.A. Kniehl, arXiv:1201.1872.
(2) B. Gong, L.-P. Wan, J.-X. Wang, and H.-F. Zhang, arXiv:1205.6682.
(3) K-T Chao, Y-Q Ma, H-S Shao, K. Wang, Y-J Zhang, arXiv:1201.2675.


Prompt ψ(2S) yields
NLO NRQCD II
CDF Data
√S = 1.96 TeV
|y_ψ(2S)|<0.6
dσ/dp_T×Br(ψ(2S)→μ+μ−) (nb)
p_T (GeV)
NLO NRQCD II
|y_ψ(2S)|<1.2(×50)
1.2<|y_ψ(2S)|<1.6
1.6<|y_ψ(2S)|<2.4(÷50)
√S = 7 TeV
CMS Data
Prompt ψ(2S) yields
d²σ/dp_Tdy×Br(ψ(2S)→μ+μ−) (nb)
p_T (GeV)
Prompt ψ(2S) yields
NLO NRQCD II
LHCb Data
√S = 7 TeV
2<y_ψ(2S)<4.5
dσ/dp_T (nb)
p_T (GeV)
ψ(2S) polarisation
NLO NRQCD II
CDF Data
√S = 1.96 TeV
|y_ψ(2S)|<0.6
λ_θ
p_T (GeV)
ψ(2S) polarisation
NLO NRQCD II
|y_ψ(2S)|<0.6
0.6<|y_ψ(2S)|<1.2
1.2<|y_ψ(2S)|<1.5
√S = 7 TeV
CMS Data
λ_θ
p_T (GeV)
ψ(2S) polarisation
NLO NRQCD
LHCb Data
√S = 7 TeV
2.5<y_ψ(2S)<4.0
λ_θ
p_T (GeV)

The landscape at the TeV scale

What's hiding behind/beyond the TeV scale ?

A few crucial questions specific to the TeV scale demand an answer and require exploration:

- **Hierarchy problem/Naturalness**
  - where is everybody else beyond the Higgs ?
- **EW dynamics above the symmetry breaking scale**
  - weakly interacting? strongly interacting ? other interactions, players ?
- **Dark matter**
  - is TeV-scale dynamics (WIMPs) at the origin of Dark Matter ?
- **Cosmological EW phase transition**
  - is it responsible for baryogenesis ?

EW phase transition and BAU

- To generate and maintain a baryon asymmetry at the EWPT we need
  - a strong 1st order phase transition:
    - impossible in the SM if $m_H > 60$ GeV
    - requires modification of Higgs potential, via H interactions with new TeV states
  - sufficient CP violation
    - not enough through CKM
    - need non-CKM CPV in the quark, lepton or Higgs sectors
    - most examples engage TeV-scale particles (for ν's could be higher)

Example

2-Higgs double models **h^0 (125), H^0, A^0, $H^\pm$**

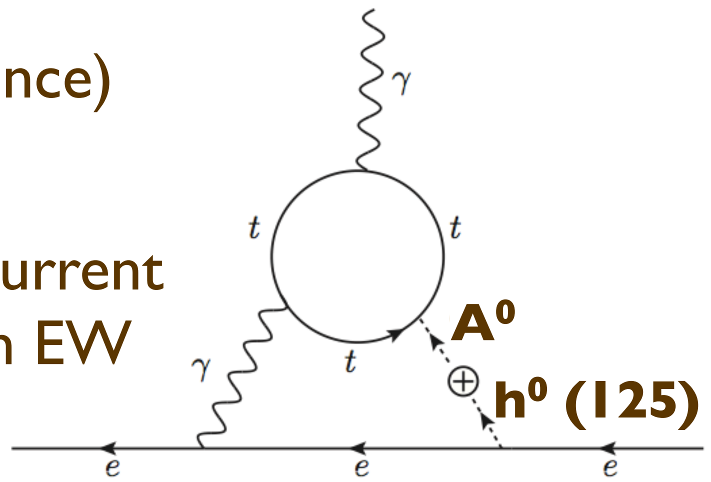
CP=1 CP=1 CP= –1

⇒ interactions among various H fields can create conditions for strong 1st order transition (Higgs vev(T_c) > T_c) - typically favours m(A^0) > 400 GeV

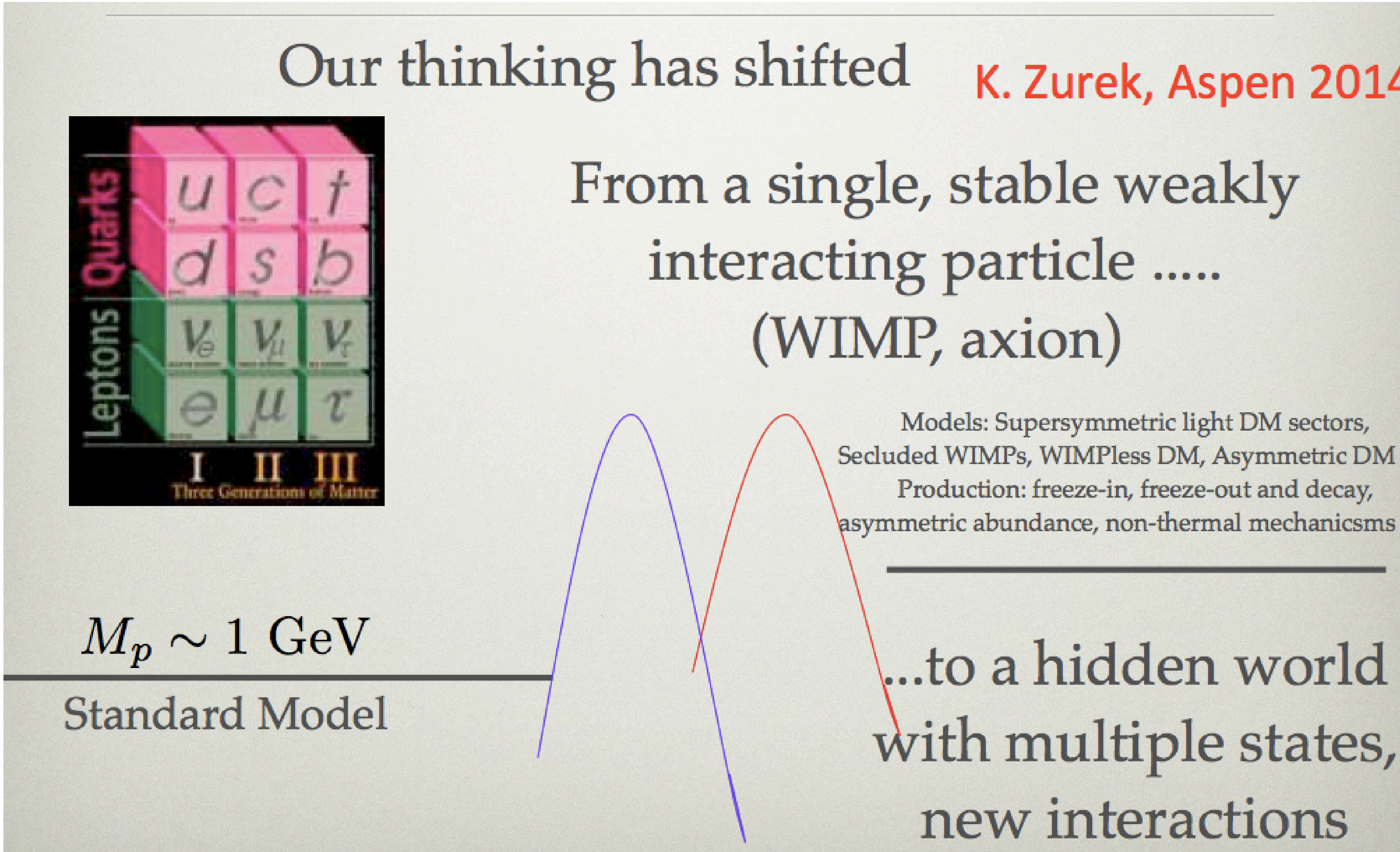
⇒ mixing of different CP states, even at few % level, is sufficient to induce enough CPV

Observables:

- additional Higgs states (direct or indirect evidence)
- h^0(125) not a CP eigenstate
- electric dipole moments (electron, neutron). Current EDM(e) close to range of CPV compatible with EW baryogenesis

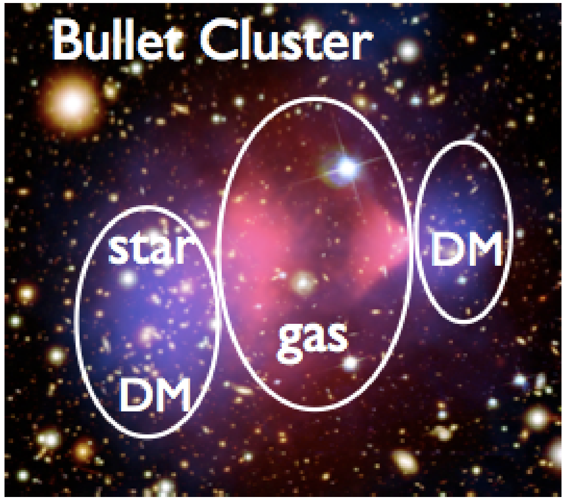


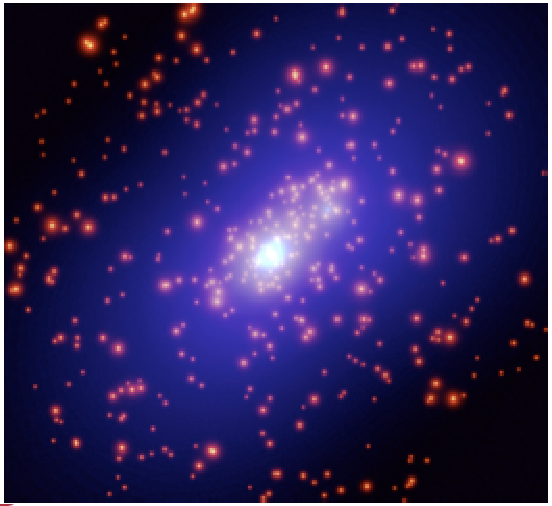
Dark Matter



ASPEN 2014: https://indico.cern.ch/event/276476/

Evidence building up for self-interacting DM





- A really large scaling cross section!

a nuclear-scale cross section

$\sigma \sim 1\,cm^2\,(m_\chi/g) \sim 2\times10^{-24}\,cm^2\,(m_\chi/GeV)$

For a WIMP: $\sigma \sim 10^{-38}\,cm^2\,(m_\chi/100\ GeV)$

SIDM indicates a new mass scale

Hai-Bo Yu, ASPEN 2014:
https://indico.cern.ch/event/276476/

More in general, interest is growing in scenarios for EWSB with rich sectors of states only coupled to the SM particles via <u>weakly interacting</u> "portals"

It is appealing to consider that they key to our puzzles lies in a tighter interplay between the DM sector, EWSB and “naturalness”.

This would be an intellectual revolution without precedents.

Uncovering or disproving a connection between DM and EWSB should remain a primary target of future programmes

Naturalness

NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS CHIRAL SYMMETRY BREAKING

G. 't Hooft

Institute for Theoretical Fysics

Utrecht, The Netherlands

Naturalness is not a recent "fashion": it's an original sin of the SM itself, first identified by one of the fathers of the SM

Aug **1979**. 23 pp.

NATO Adv.Study Inst.Ser.B Phys. 59 (1980) 135

As we will see, naturalness will put the severest restriction on the occurrence of scalar particles in renormalizable theories. In fact we conjecture that this is the reason why light, weakly interacting scalar particles are not seen.

Pursuing naturalness beyond 1000 GeV will require theories that are immensely complex compared with some of the grand unified schemes.

We're finally there, at 1 TeV, facing the fears about a light SM Higgs anticipated long ago

A remarkable attempt towards a natural theory was made by Dimopoulos and Susskind [2)]. These authors employ various kinds of confining gauge forces to obtain scalar bound states which may substitute the Higgs fields in the conventional schemes. In their model the observed fermions are still considered to be elementary.

Most likely a complete model of this kind has to be constructed step by step. One starts with the experimentally accessible aspects of the Glashow-Weinberg-Salam-Ward model. This model is natural if one restricts oneself to mass-energy scales below 1000 GeV. Beyond 1000 GeV one has to assume, as Dimopoulos and Susskind do, that the Higgs field is actually a fermion-antifermion composite field. Coupling this field to quarks and leptons in order to produce their mass, requires new scalar fields that cause naturalness to break down at 30 TeV or so.

- The observation of the Higgs where the SM predicted it would be, its SM-like properties, and the lack of BSM phenomena up to the TeV scale, make the naturalness issue as puzzling as ever
- Whether to keep believing in the MSSM or other specific BSM theories after LHC@8TeV is a matter of personal judgement. But the broad issue of naturalness will ultimately require an understanding.

➡ **The future of accelerator physics should be tailored to address this question**

Remarks

- **Our field has other open puzzles, associated e.g. to**
  - **neutrinos**
  - **flavour**
  - **axion**
  - **...**

- **These puzzles hint at scales that are typically much larger than O(TeV), even as large as the GUT scale**

- **The complete understanding of TeV-scale physics is necessary to put in perspective and properly interpret the information about those high scales that may come from indirect probes (neutrinos, p-decay, coupling unification, ...)**

Remarks

- Despite the relevance of these questions, and the conviction that they will find an answer, there is no guarantee that such answer will come soon.
- There is no absolute no-lose theorem in sight, pointing with absolute certainty to a given experimental facility
- The planning of future facilities may need to be driven by the exploratory spirit that characterized the golden age of particle physics.
- But the directions are clear:
  - higher-precision studies (of Higgs sector, of EW interactions)
  - higher energy (push the search for "everyone else")

Precision physics at the LHC

The LHC timeline

Spring 2015 → 2017	Winter 2018 → 2019	Spring 2020 → 2022	Winter 2021 → 2023	Spring 2023 → 2032
$\sqrt{S} \to 13\text{-}14$ TeV	shutdown	$\sqrt{S} = 14$ TeV	shutdown	$\sqrt{S} = 14$ TeV
$\int L \sim 100\ \mathrm{fb}^{-1}$		$\int L \sim 300\ \mathrm{fb}^{-1}$		$\int L \sim 3000\ \mathrm{fb}^{-1}$

Ex: Future precision in the determination of Higgs coupling ratios

L(fb^{-1})	Exp.	$\kappa_g \cdot \kappa_Z / \kappa_H$	κ_γ/κ_Z	κ_W/κ_Z	κ_b/κ_Z	κ_τ/κ_Z	κ_Z/κ_g	κ_t/κ_g	κ_μ/κ_Z	$\kappa_{Z\gamma}/\kappa_Z$
300	ATLAS	[3,6]	[5,11]	[4,5]	N/a	[11,13]	[11,12]	[17,18]	[20,22]	[78,78]
	CMS	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	ATLAS	[2,5]	[2,7]	[2,3]	N/a	[7,10]	[5,6]	[6,7]	[6,9]	[29,30]
	CMS	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

Table 1. Estimated precision on the measurements of ratios of Higgs boson couplings. These values are obtained at $\sqrt{s}$ = 14 TeV using an integrated dataset of 300 fb^{-1} at LHC, and 3000 fb^{-1} at HL-LHC. Numbers in brackets are % uncertainties on couplings for [no theory uncertainty, current theory uncertainty] in the case of ATLAS and for [Scenario2, Scenario1] in the case of CMS.

CMS Scenario 1: same systematics as 2012 (TH and EXP)
CMS Scenario 2: half the TH syst, and scale with 1/sqrt(L) the EXP syst

Note: assume no invisible Higgs decay contributing to the Higgs width

Note: results of scenario 2 @ 3000/fb are overall as powerful as LC@500GeV !!

Current challenges for the field: precision

Theoretical uncertainties on production rates (Higgs XS WG, arXiv:1101.0593)

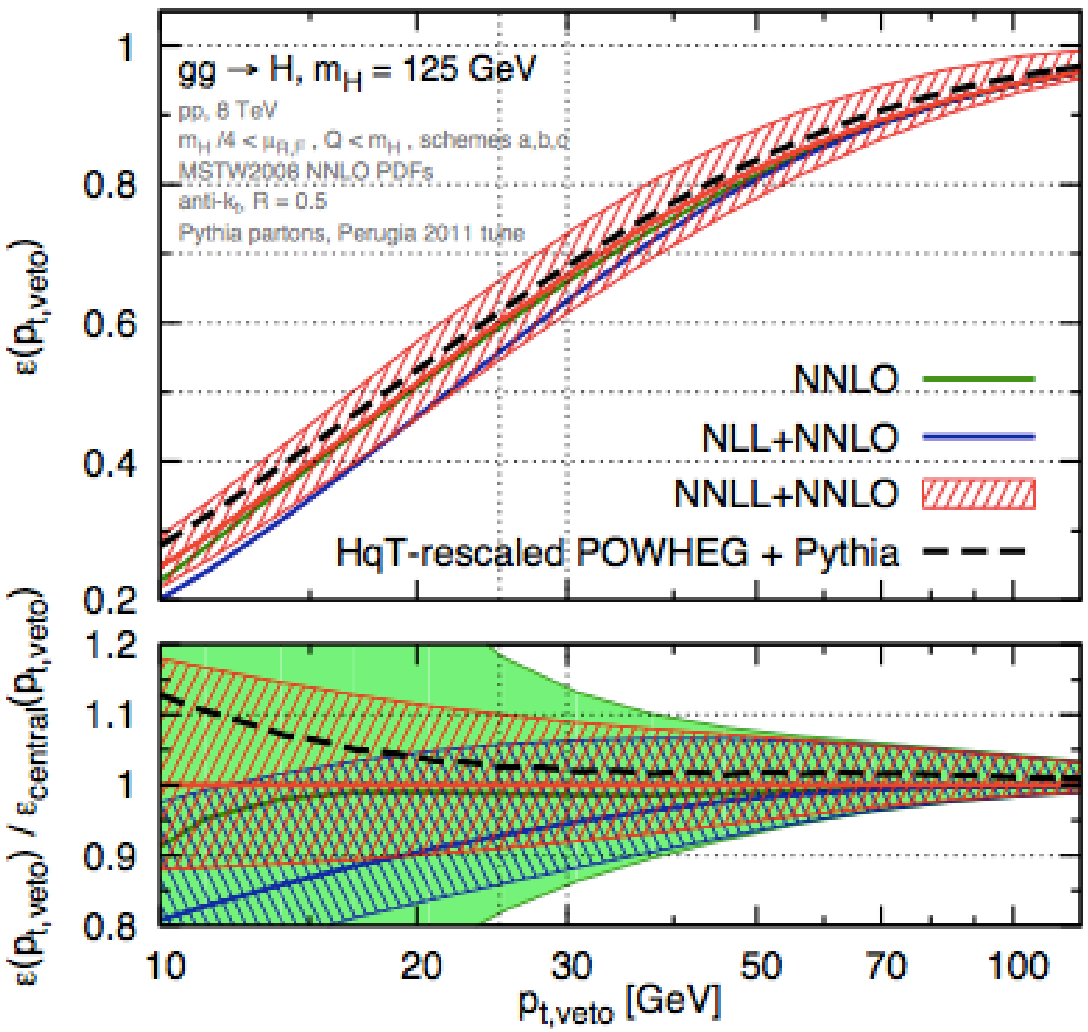
14 TeV	δ(pert. theory)	δ(PDF, α_S)
$gg \to H$	± 10 %	± 7%
VBF ($WW \to H$)	± 1 %	± 2%
$qq \to WH$	± 0.5 %	± 4%
$(qq,gg) \to ZH$	± 2 %	± 4%
$(qq,gg) \to ttH$	± 8 %	± 9%

Improve with higher-loop calculations:
gg->H @ NNNLO
ttH @ NNLO

Improve with dedicated QCD measurements, and appropriate calculations

Current challenges for the field: accurate description of final states

- to properly model experimental selection cuts
- to properly model the separation between signals and background
- to improve the sensitivity to rare and "stealthy" final states in BSM searches

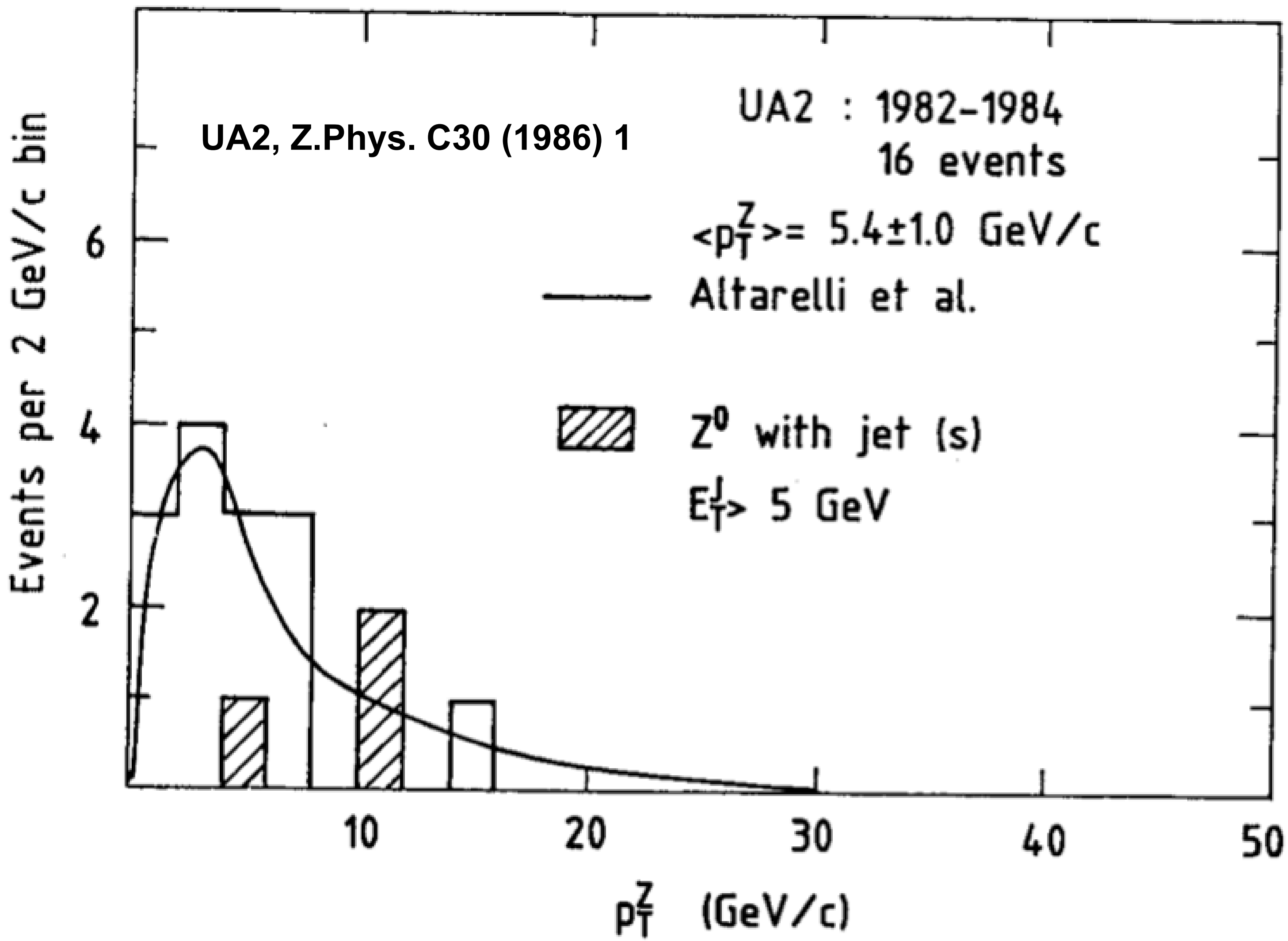


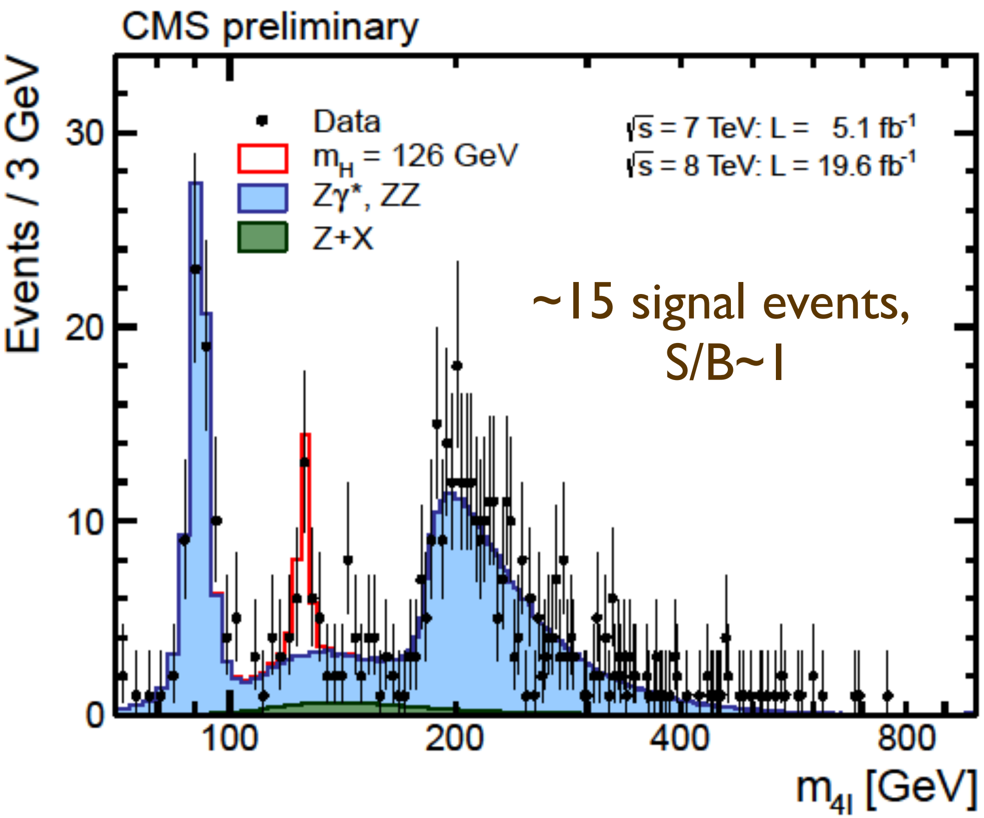
Ex. jet veto efficiency, required to reduce bg's to H→WW*

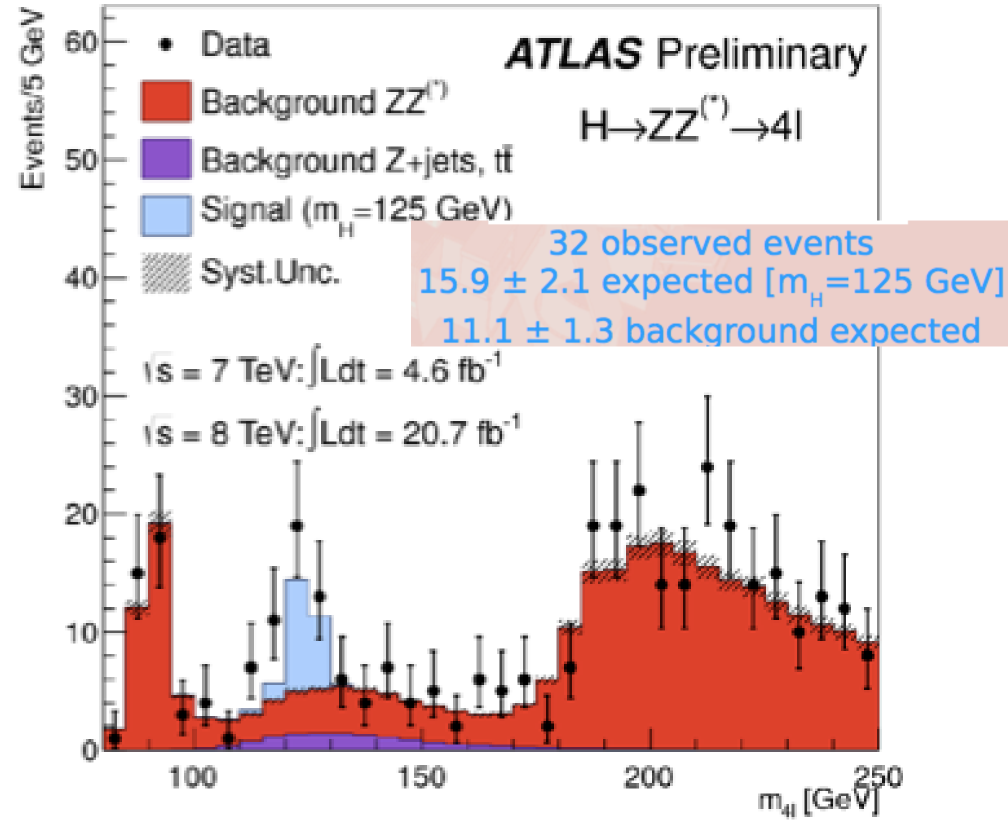
Banfi, Monni, Salam, Zanderighi, arXiv:1206.4998

Towards experimental constraints on Higgs production dynamics ....

To put it in perspective, W/Z physics started like this ....., from a score of events:



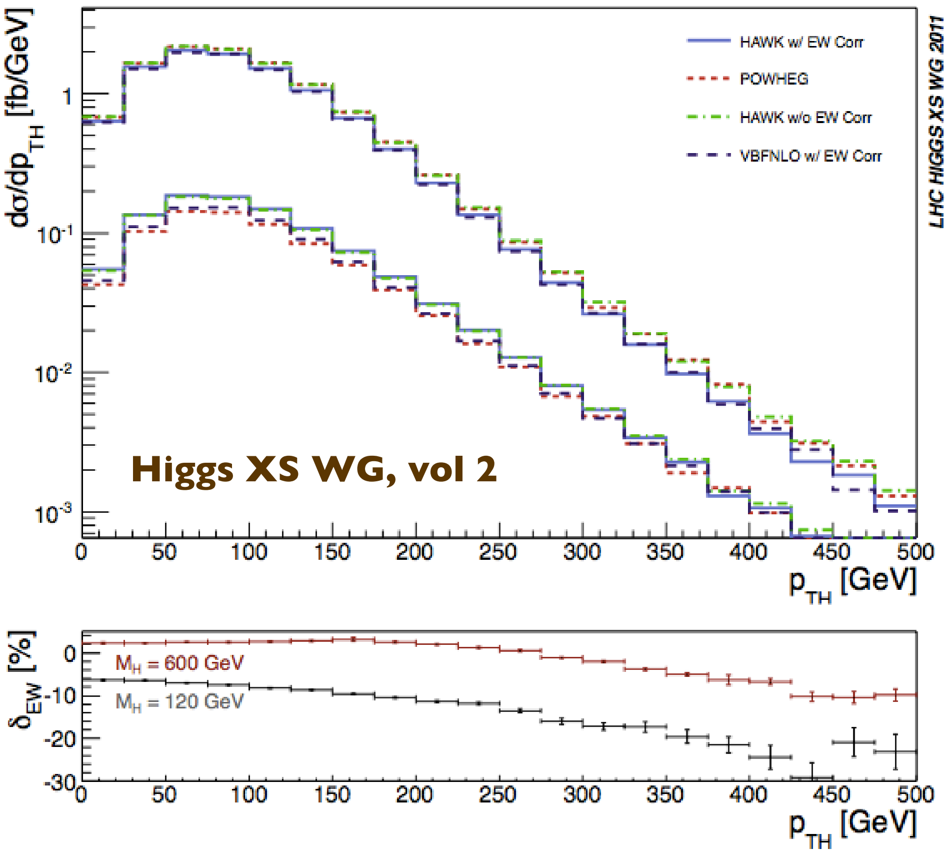




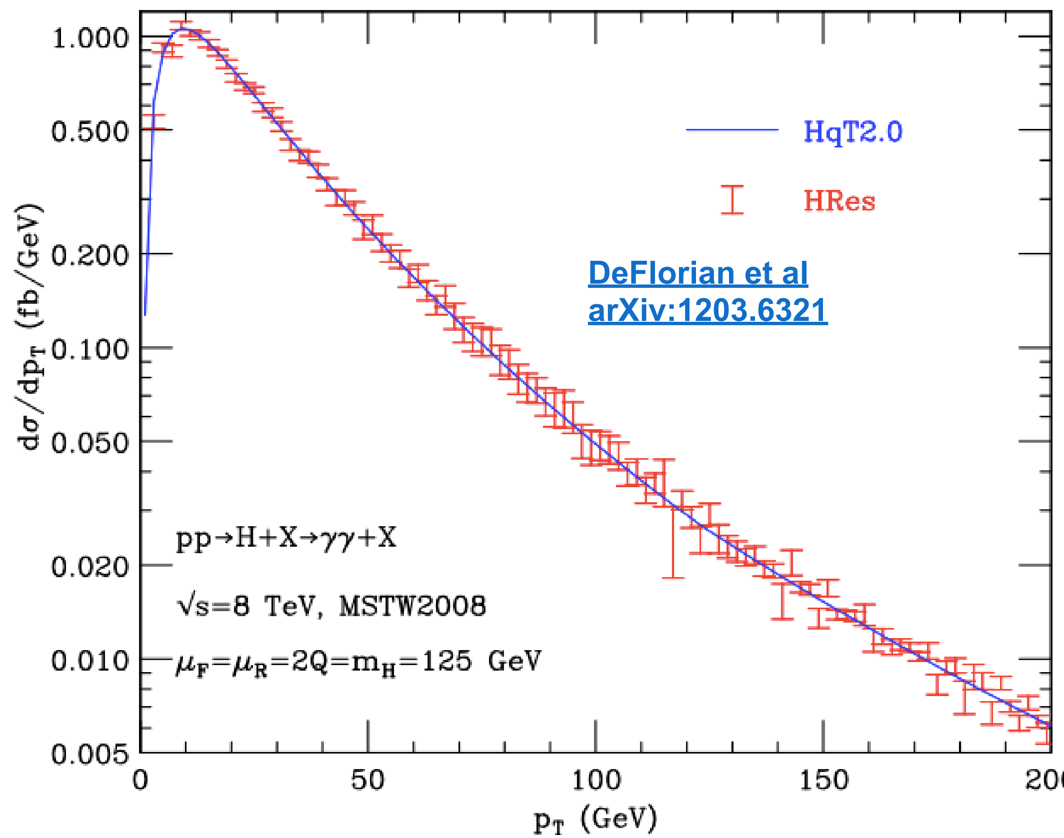
There is enough to start plotting pt(H), N_{jet} distribution in H production, etc.

p_T(H): qq → qq H vs gg → H

qq → qq H



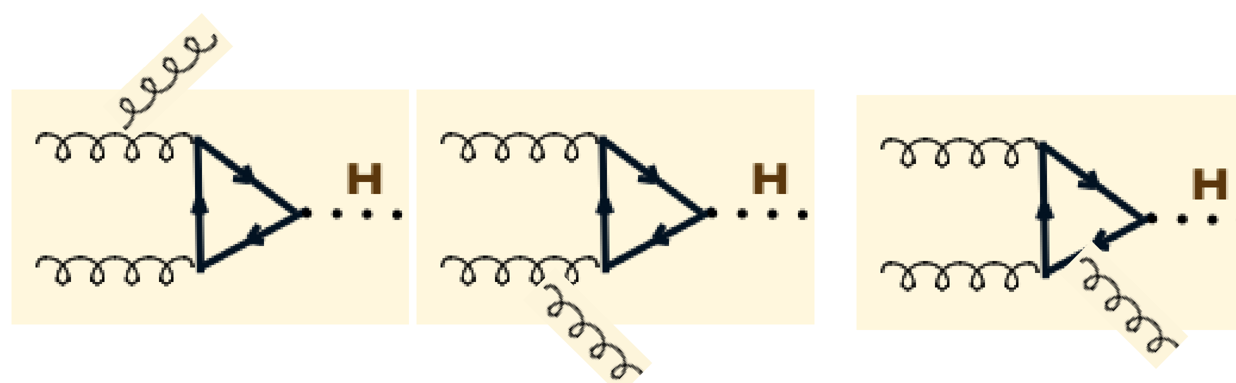
gg → H



- p_T(peak)~60 GeV
- Large size of EW corrections

- p_T(peak)~10 GeV

gg→H at p_T > m_{top} resolves the inside of the production triangle, an alternative probe to its components



Recent progress in NNLO

- **Two long-awaited milestone calculations in progress, delivering first results:**

  - **Jet production**. Completed so far:

    - gg initial state: A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover, J. Pires, **arXiv:1301.7310**

  - **σ(tt)** (Czakon, Mitov et al): full results available for total cross section, at NNLO+NNLL

    Baernreuther, Czakon, Mitov arXiv:1204.5201
    Czakon, Mitov arXiv:1207.0236
    Czakon, Mitov arXiv:1210.6832
    Czakon, Fiedler, Mitov arXiv:1303.6254

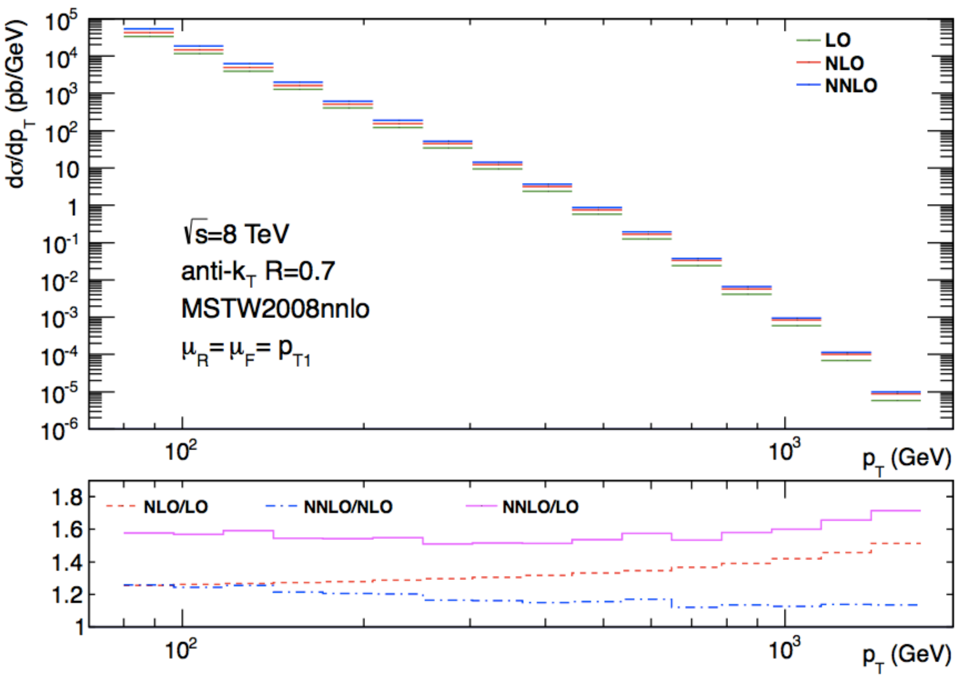
    - implemented in a numerical code

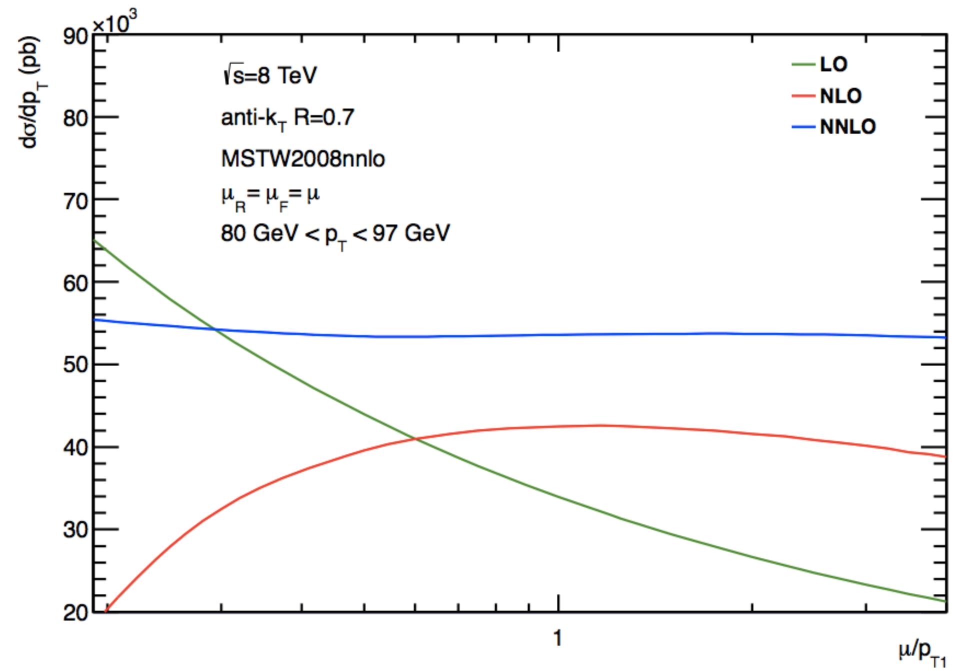
      Top++: Czakon, Mitov arXiv:1112.5675

    - first NNLO result for production of coloured final state in hadron collisions, first direct probe of gluon PDF known to NNLO

Inclusive jet cross section at NNLO

"Second order QCD corrections to jet production at hadron colliders: the all-gluon contribution", A. Gehrmann-De Ridder, T. Gehrmann, E.W. N. Glover, J. Pires, arXiv:1301.7310





NNLO/NLO ~ 1.2

NNLO scale systematics ~ few % ...
- does this survive if $\mu_F \neq \mu_R$?

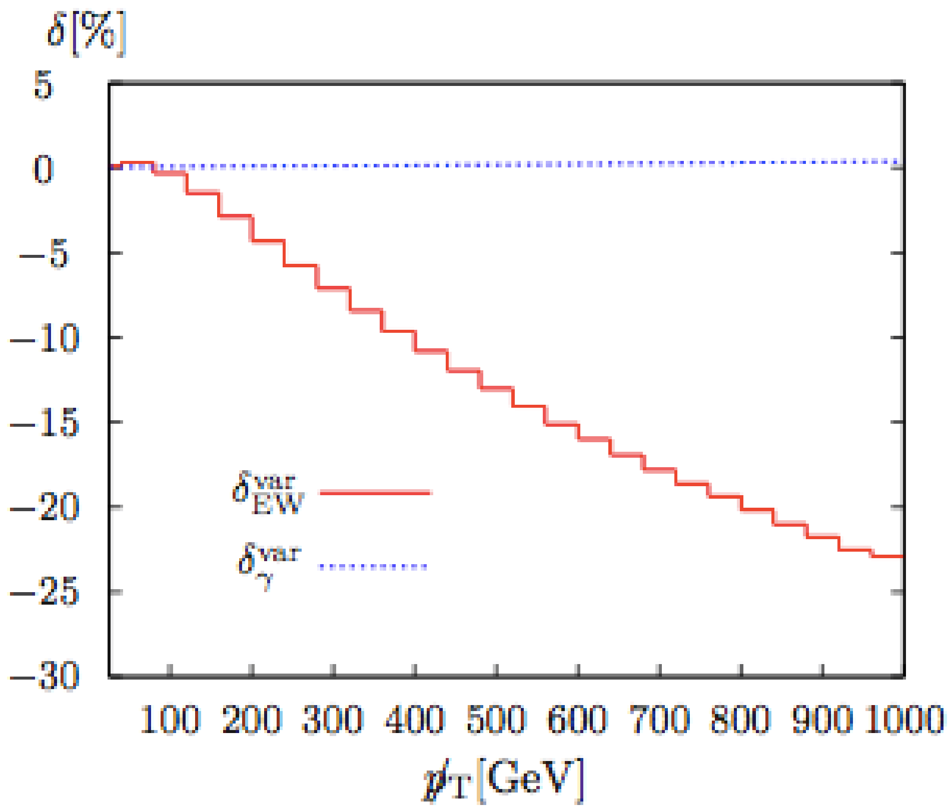
Notice that NNLO outside the NLO scale-variation band

At this level of precision, there are other things one should start considering. E.g. non-perturbative systematics and EW corrections

Impact of EW radiative corrections, example:

Jet+MET spectrum from ($Z \to \nu\nu$)+jet: corrections due to pure EW and pure EM corrections

Denner, Dittmaier, Kasprzik, Mück, arxiv:1211.5078v2

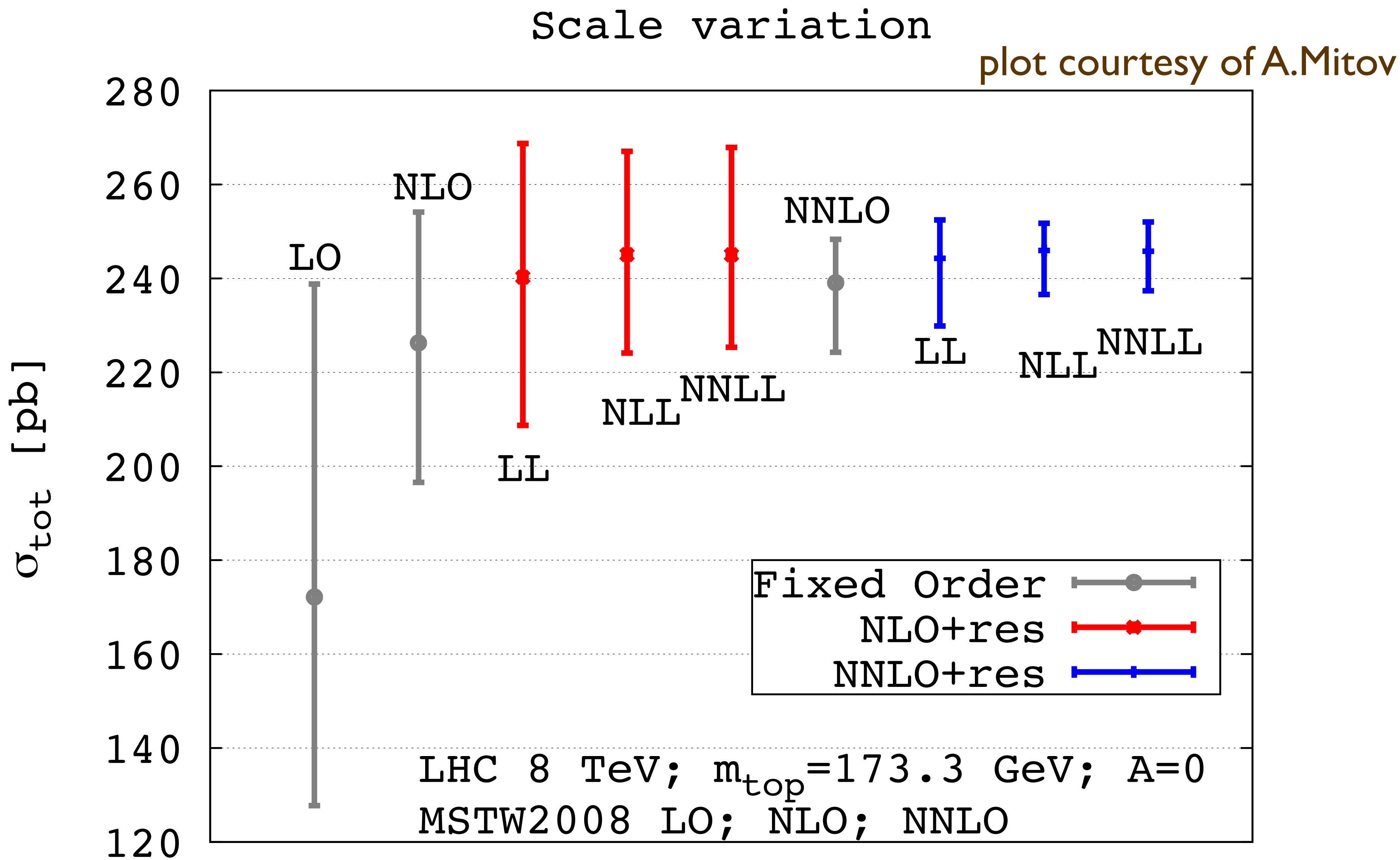


Unless EW corrections are included in the calculations, we might end up removing possible differences between data and QCD predictions for the Z pt spectrum by retuning the QCD MCs!

Very-high pt data on the Z pt spectrum are crucial to assess that the effect is indeed so large!

How does one convince himself that possible deviations of this size from the QCD expectation are indeed the result of EW corrections ?

Inclusive ttbar cross section at NNLO

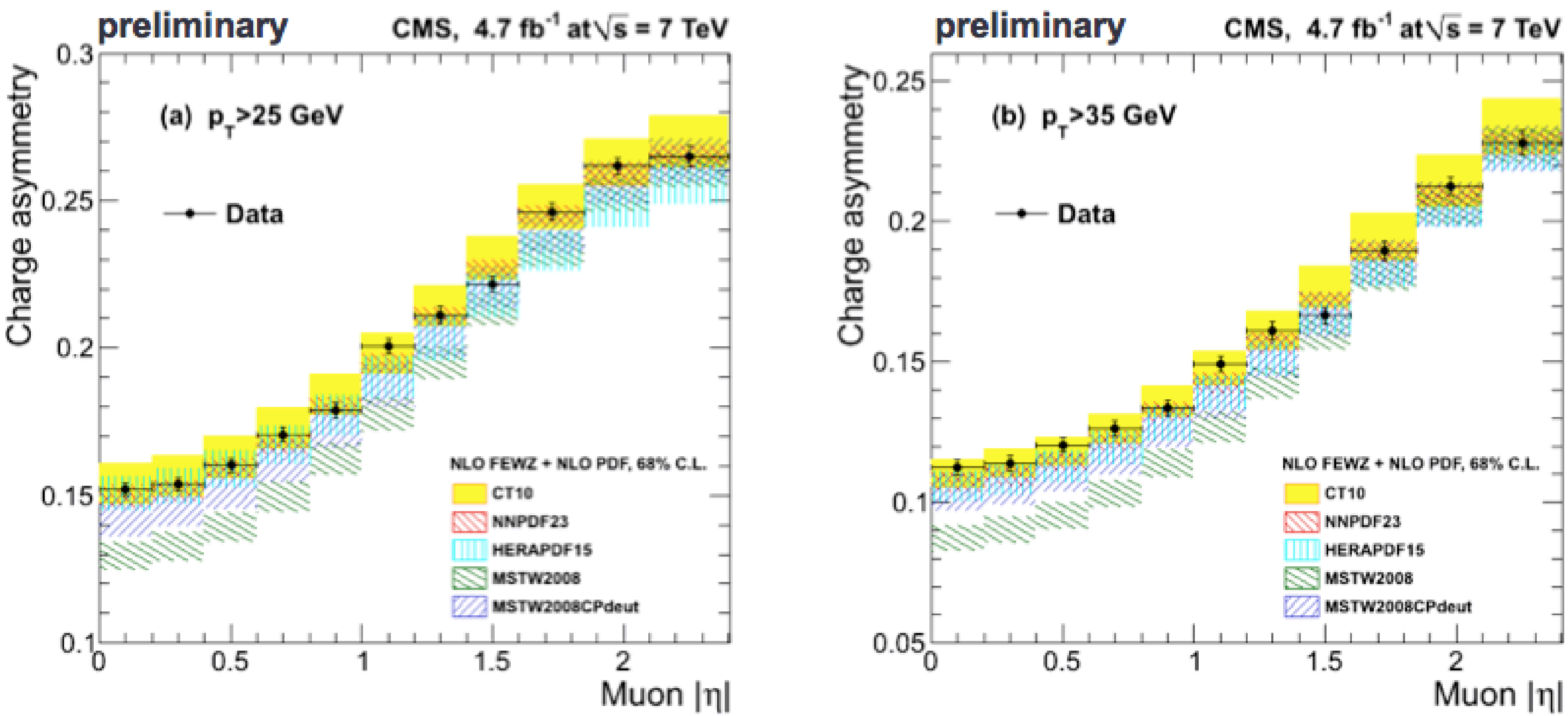


Independent μ_R , μ_F variation, with $\mu_0 = m_{top}$,
$0.5\ \mu_0 < \mu_{R,F} < 2\ \mu_0$ and
$0.5 < \mu_R / \mu_F < 2$

Improving the PDF systematics using LHC data

There is still room to further constrain PDF distributions relevant for W/Z production properties.

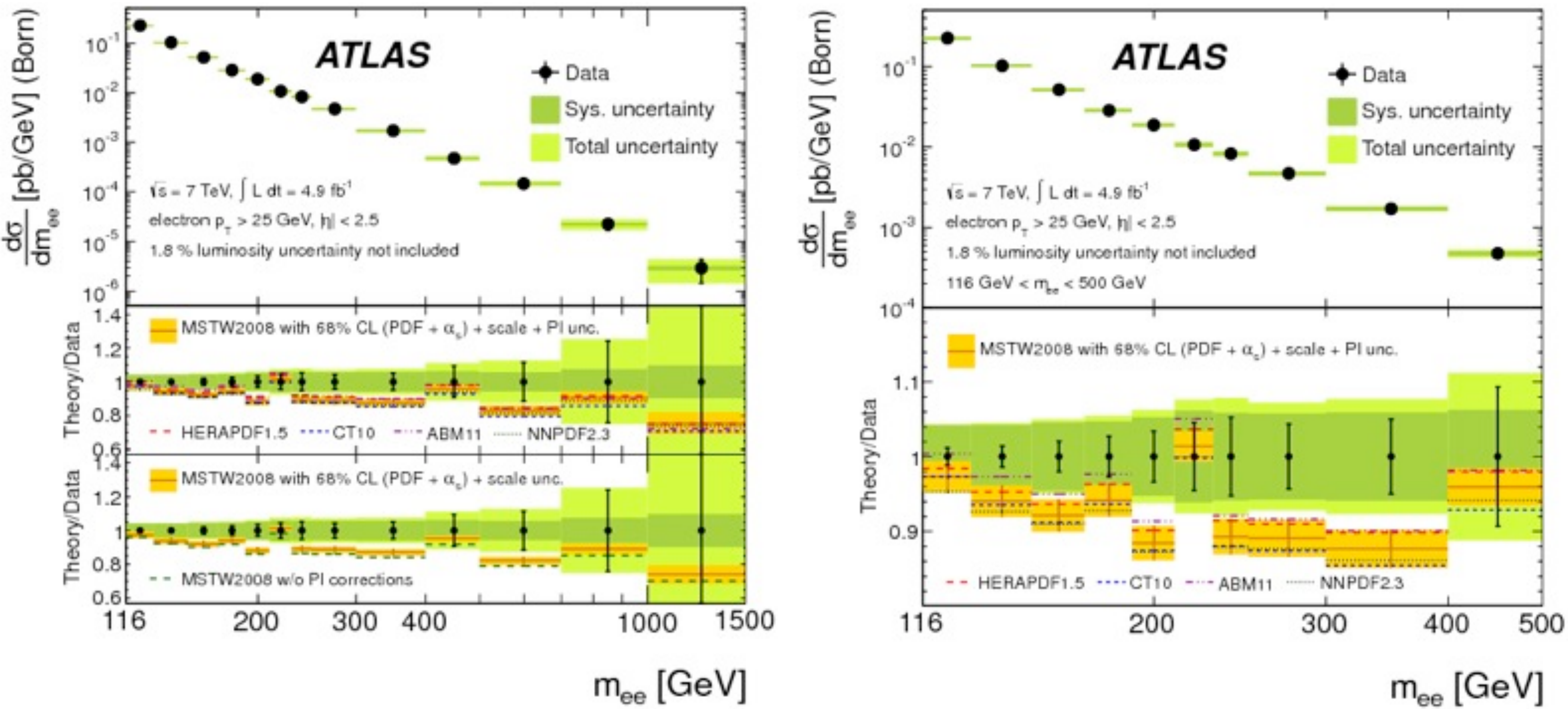
CMS-PAS-SMP-12-021



Questions:

- How do we convince ourselves that we are actually fitting the PDFs, and not missing higher-order QCD or EW effects in the matrix elements?
- Would this have an impact in the extraction of m_W ?

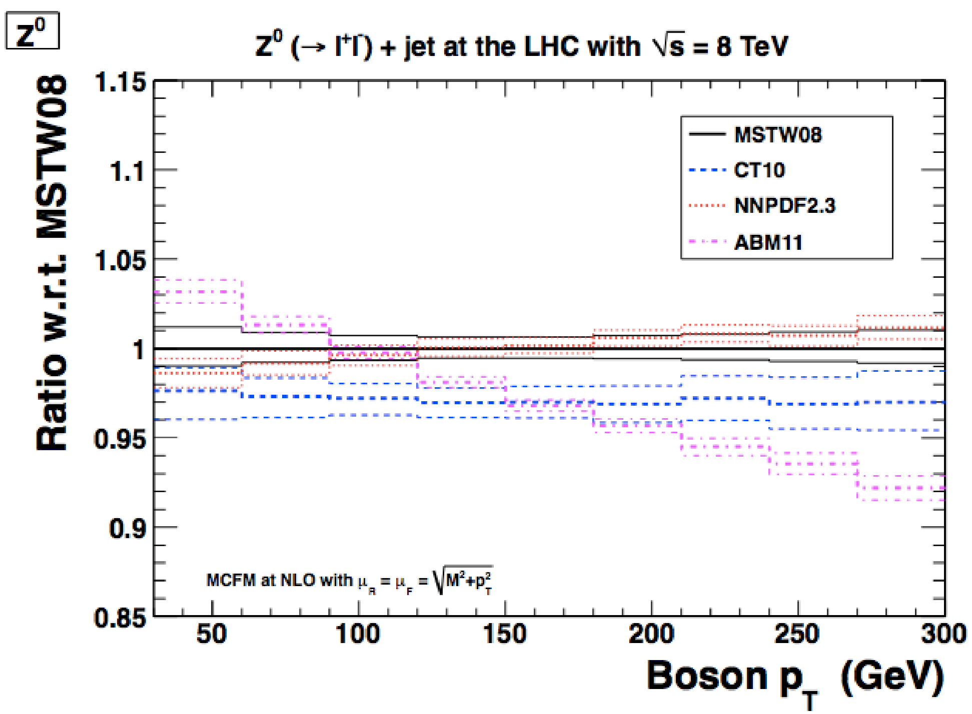
High-mass DY cross sections and PDFs

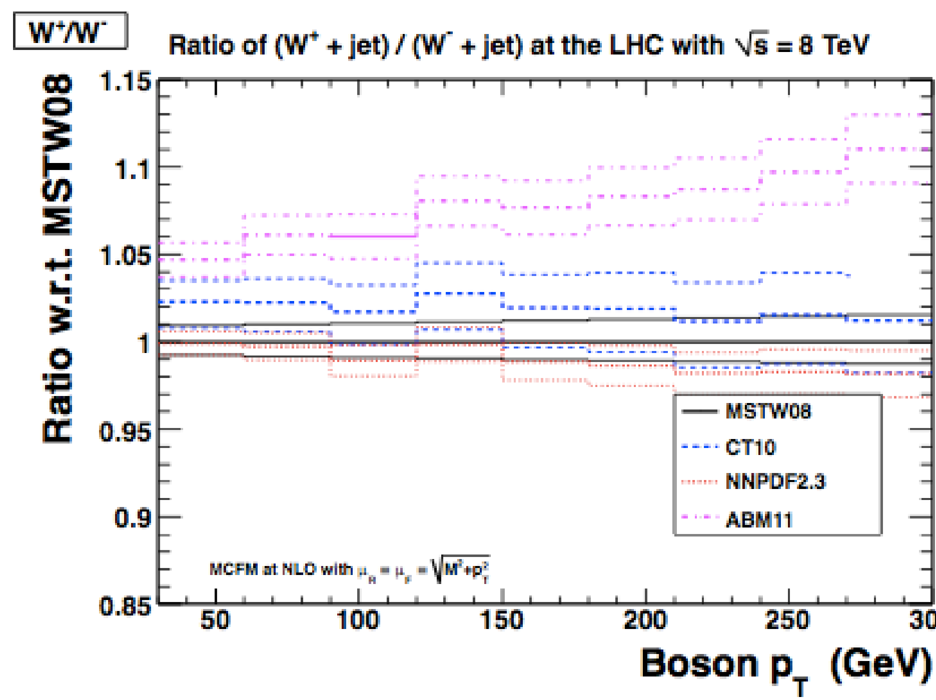


ATLAS, Phys.Lett. B725 (2013) 223-242 arXiv:1305.4192

Large-pt production of gauge bosons as a probe of gluon PDF in the region of relevance to gg→H production

S.Malik and G.Watt, arXiv:1304.2424



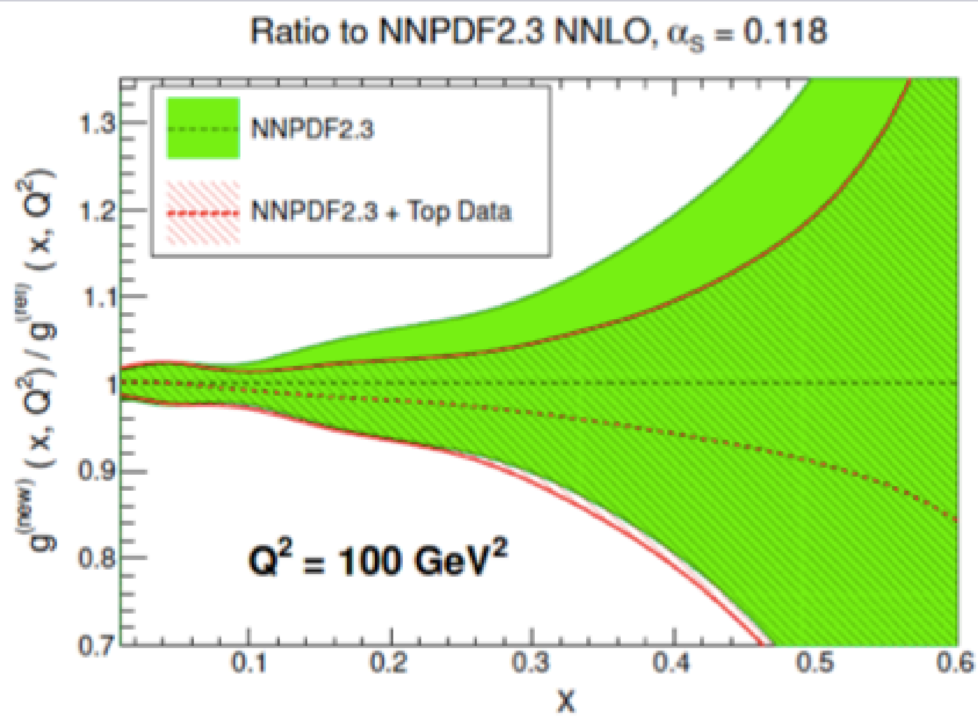


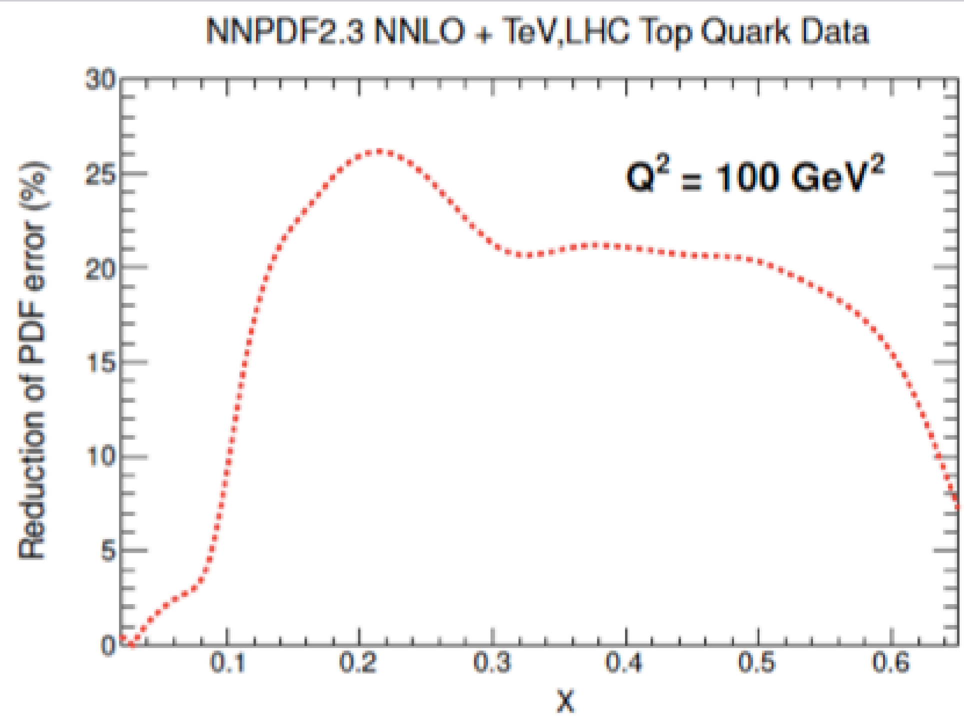
⇒ excellent motivation to undertake the calculation of $d\sigma/dp_T(V)$ at NNLO !!

Constraining the gluon PDF with $\sigma(tt)$

M. Czakon et al arXiv:1303.7215

- Top quark cross-section data **discriminates between PDF sets**
- In addition, it can also be used to **reduce the PDF uncertainties** within a single PDF set
- We included the most precise top quark data into the **NNPDF2.3** global PDF analysis





Collider	Ref	Ref+TeV	Ref +TeV+LHC7	Ref+TeV+LHC7+8
Tevatron	7.26 ± 0.12	-	-	-
LHC 7 TeV	172.5 ± 5.2	172.7 ± 5.1	-	-
LHC 8 TeV	247.8 ± 6.6	248.0 ± 6.5	245.0 ± 4.6	-
LHC 14 TeV	976.5 ± 16.4	976.2 ± 16.3	969.8 ± 12.0	969.6 ± 11.6

8TeV/7TeV and 14TeV/8TeV cross section ratios: the ultimate precision

MLM and J.Rojo, arXiv:1206.3557

$E_{1,2}$: different beam energies

X,Y: different hard processes

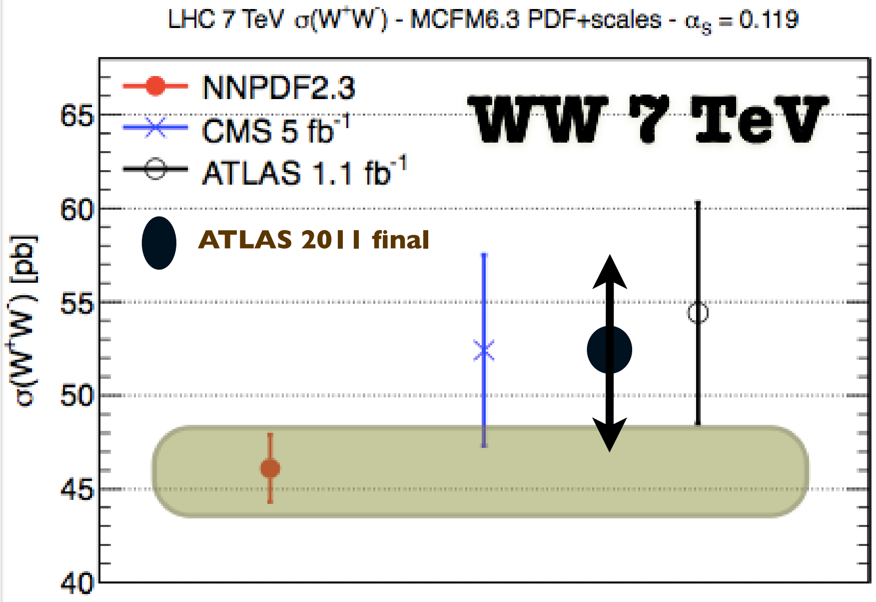
$$R_{E_2/E_1}(X) \equiv \frac{\sigma(X, E_2)}{\sigma(X, E_1)} \longrightarrow$$

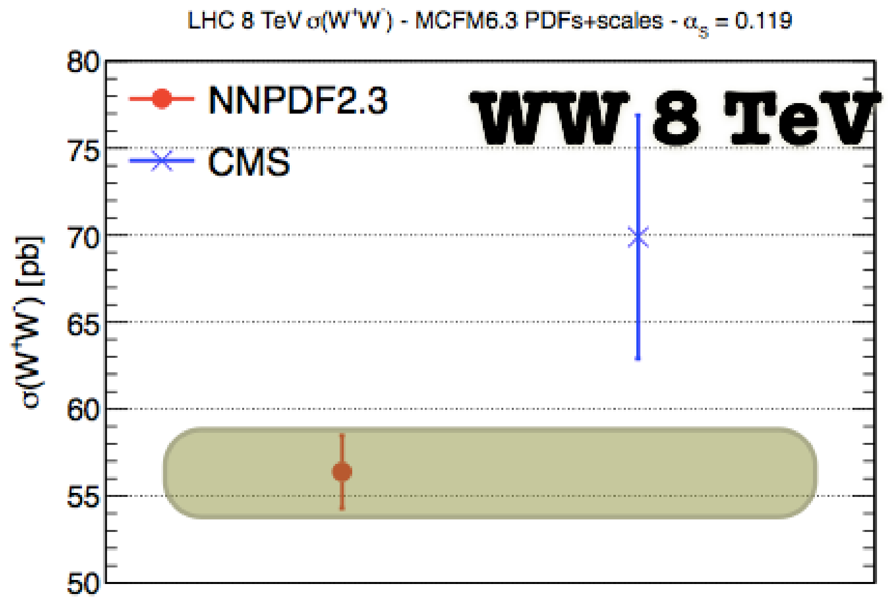
- TH: reduce "scale uncertainties"
- TH: reduce parameters' systematics: PDF, m_{top}, α_S, ... at E_1 and E_2 are fully correlated
- TH: reduce MC modeling uncertainties
- EXP: reduce syst's from acceptance, efficiency, JES, ...

$$R_{E_2/E_1}(X, Y) \equiv \frac{\sigma(X, E_2)/\sigma(Y, E_2)}{\sigma(X, E_1)/\sigma(Y, E_1)} \equiv \frac{R_{E_2/E_1}(X)}{R_{E_2/E_1}(Y)} \longrightarrow$$

- TH: possible further reduction in scale and PDF syst's
- EXP: no luminosity uncertainty
- EXP: possible further reduction in acc, eff, JES syst's (e.g. $X,Y=W^+,W^-$)

Following results obtained using best available TH predictions: NLO, NNLO, NNLL resummation when available





Diboson cross section ratios

8 over 7 TeV	$R^{\text{th,nnpdf}}$	$\delta_{\text{PDF}}(\%)$	$\delta_{\text{scales}}\ (\%)$	
WW	1.223	$\pm\ 0.1$	$-0.4 - 0.2$	
$gg \to WW$	1.330	$\pm\ 0.2$	$-0.0 - 0.0$	(scale errors missing)
WW/W	1.057	$\pm\ 0.1$	$-0.3 - 0.2$	
WZ	1.209	$\pm\ 0.4$	$-1.2 - 0.4$	
ZZ	1.165	$\pm\ 0.4$	$-0.6 - 1.1$	
$gg \to ZZ$	1.218	$\pm\ 1.2$	$-0.0 - 0.0$	(scale errors missing)
ZZ/Z	1.000	$\pm\ 0.4$	$-0.5 - 1.1$	
WW/WZ	1.012	$\pm\ 0.4$	$-0.2 - 1.0$	
WW/ZZ	1.050	$\pm\ 0.4$	$-0.9 - 0.7$	
WZ/ZZ	1.038	$\pm\ 0.5$	$-1.7 - 0.4$	

14 TeV / 8 TeV: NNPDF results

CrossSection	$r^{th,nnpdf}$	$\delta_{PDF}(\%)$	δ_{α_s} (%)	δ_{scales} (%)
$t\bar{t}/Z$	2.121	1.01	−0.84 − 0.75	0.42 − 1.10
$t\bar{t}$	3.901	0.84	−0.51 − 0.66	0.38 − 1.07
Z	1.839	0.37	−0.10 − 0.34	0.28 − 0.18
W^+	1.749	0.41	−0.03 − 0.27	0.31 − 0.18
W^-	1.859	0.39	−0.08 − 0.26	0.32 − 0.13
W^+/W^-	0.941	0.28	0.00 − 0.05	0.00 − 0.04
W/Z	0.976	0.09	−0.07 − 0.04	0.04 − 0.02
ggH	2.564	0.36	−0.10 − 0.09	0.89 − 0.98
$ggH/t\bar{t}$	0.657	0.75	−0.56 − 0.41	1.38 − 1.05
$t\bar{t}(M_{tt} \geq 1\text{TeV})$	8.215	2.09	0.00 − 0.00	1.61 − 2.06
$t\bar{t}(M_{tt} \geq 2\text{TeV})$	24.776	6.07	0.00 − 0.00	3.05 − 1.07
$\sigma\text{jet}(p_T \geq 1\text{TeV})$	15.235	1.72	0.00 − 0.00	2.31 − 2.19
$\sigma\text{jet}(p_T \geq 2\text{TeV})$	181.193	6.75	0.00 − 0.00	3.66 − 5.76

- $\delta<10^{-2}$ in $W^\pm$ ratios: absolute calibration of 14 vs 8 TeV lumi
- $\delta\sim10^{-2}$ in $\sigma(tt)$ ratios
- $\delta_{scale} < \delta_{PDF}$ at large p_T^{jet} and M_{tt}: constraints on PDFs

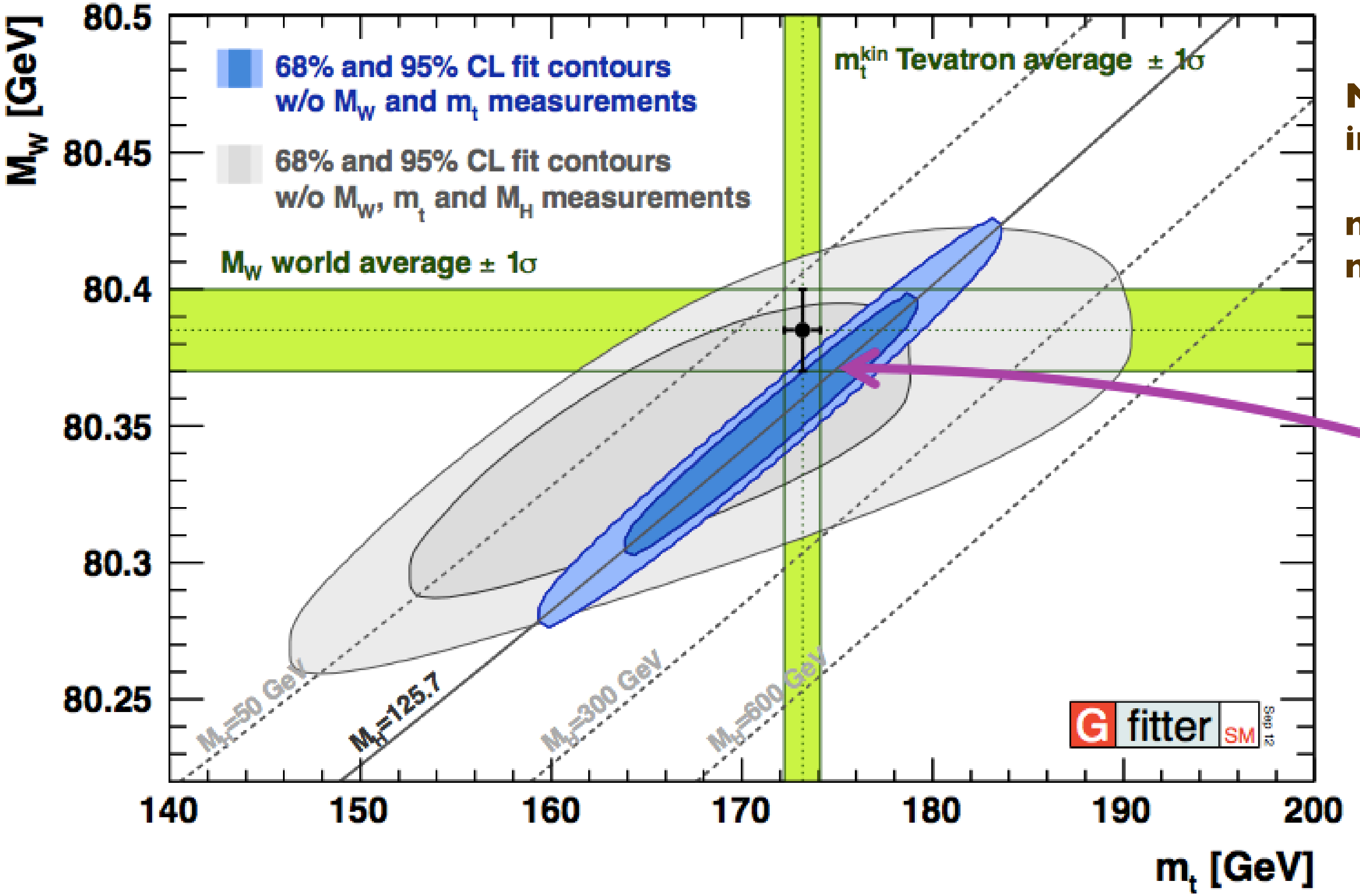
14 TeV / 8 TeV: NNPDF vs MSTW vs ABKM

Ratio	$r^{th,nnpdf}$	$\delta_{PDF}(\%)$	$r^{th,mstw}$	$\delta_{PDF}(\%)$	$\Delta^{mstw}(\%)$	$r^{th,abkm}$	$\delta_{ABKM}(\%)$	Δ^{abkm} (%)
$t\bar{t}/Z$	2.121	1.01	2.108	0.95	0.93	2.213	1.87	-3.99
$t\bar{t}$	3.901	0.84	3.874	0.91	0.97	4.103	1.87	-4.90
Z	1.839	0.37	1.838	0.41	0.04	1.855	0.34	-0.87
W^+	1.749	0.41	1.749	0.49	0.03	1.767	0.30	-0.98
W^-	1.859	0.39	1.854	0.42	0.21	1.879	0.32	-1.11
W^+/W^-	0.941	0.28	0.943	0.19	-0.19	0.940	0.13	0.13
W/Z	0.976	0.09	0.976	0.10	0.03	0.977	0.10	-0.14
ggH	2.564	0.36	2.572	0.57	-0.30	2.644	0.66	-3.12
$ggH/t\bar{t}$	0.657	0.75	0.000	0.00	0.00	0.000	0.00	0.00
$t\bar{t}(M_{tt} \geq 1\text{TeV})$	8.215	2.09	7.985	2.02	3.12	8.970	3.58	-8.83
$t\bar{t}(M_{tt} \geq 2\text{TeV})$	24.776	6.07	23.328	4.32	6.05	23.328	4.93	6.05
$\sigma\text{jet}(p_T \geq 1\text{TeV})$	15.235	1.72	15.193	1.62	-1.33	14.823	1.84	1.13
$\sigma\text{jet}(p_T \geq 2\text{TeV})$	181.193	6.75	191.208	3.34	-6.52	174.672	4.94	2.69

- Several examples of 3-4σ discrepancies between predictions of different PDF sets, even in the case of W and Z rates

Top quark and W mass

Inclusion of m_H in EW fits greatly tightens correlation between m_W and m_{top}
introducing perhaps a slight tension ?



New EW fit results, including m_{Higgs} :

$m_{top} = 175.8^{+2.7}_{-2.4}$ GeV
$m_W = 80359 \pm 11$ MeV

Continued improvement in the direct determination of m_W and m_{top} remains a **high priority**

Tevatron combined W mass: M_W =80387±16 MeV

Tevatron+LEP2 combined W mass: M_W =80385±15 MeV

Uncertainties

Uncertainty	D0	CDF
Lepton energy scale/resn/modelling	17	7
Hadronic recoil energy scale and resolution	5	6
Backgrounds	2	3
Parton distributions	11	10
QED radiation	7	4
$p_T(W)$ model	2	5
Total systematic uncertainty	22	15
W-boson statistics	13	12
Total uncertainty	26 MeV	19 MeV

Largely stat. in origin → **10 MeV**

Largely theory in origin → **12 MeV**

90% of M_W information is in transverse mass

Top quark mass

Tevatron combination:

$$m_{top} = 173.20 \pm 0.51\ (\text{stat}) \pm 0.71\ (\text{syst}) = 173.20 \pm 0.87\ \text{GeV}$$

LHC combination:

TOPLHC NOTE

ATLAS-CONF-2013-102
CMS PAS TOP-13-005

September 15, 2013

Combination of ATLAS and CMS results on the mass of the top-quark using up to 4.9 fb^{-1} of $\sqrt{s} = 7$ TeV LHC data

The ATLAS and CMS Collaborations

$$m_{top} = 173.29 \pm 0.23\ (\text{stat}) \pm 0.92\ (\text{syst}) = 173.29 \pm 0.95\ \text{GeV}$$

World average:

LHC/Tevatron NOTE

ATLAS-CONF-2014-008
CDF Note 11071
CMS PAS TOP-13-014
D0 Note 6416

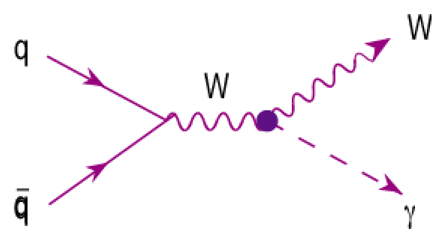
March 17, 2014

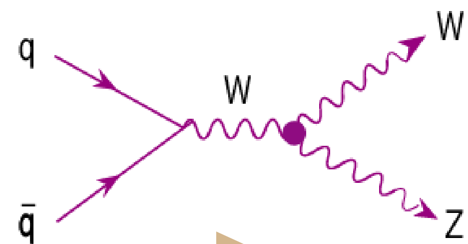
First combination of Tevatron and LHC measurements of the top-quark mass

$$m_{top} = 173.29 \pm 0.27\ (\text{stat}) \pm 0.71\ (\text{syst}) = 173.29 \pm 0.76\ \text{GeV}$$

Precise determinations of the self-couplings of EW gauge bosons

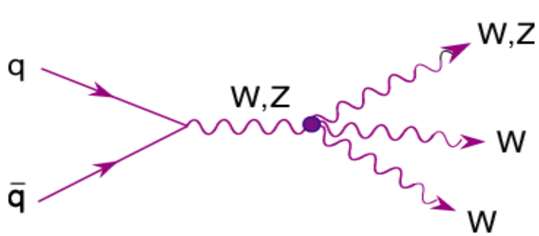
5 parameters describing weak and EM dipole and quadrupole moments of gauge bosons. The SM predicts their value with accuracies at the level of **10^{-3}**, which is therefore the goal of the required experimental precision

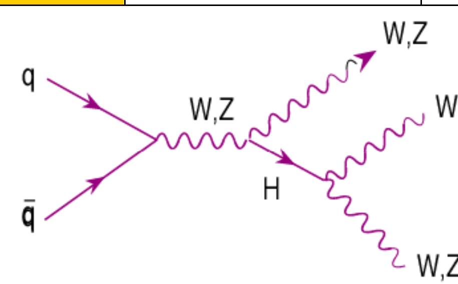


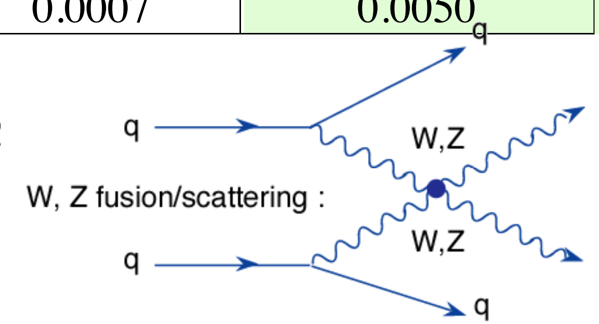


LHC options

Coupling	14 TeV 100 fb^{-1}	14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	28 TeV 1000 fb^{-1}	LC 500 fb^{-1}, 500 GeV
λ_γ	0.0014	0.0006	0.0008	0.0002	0.0014
λ_Z	0.0028	0.0018	0.0023	0.009	0.0013
$\Delta\kappa_\gamma$	0.034	0.020	0.027	0.013	0.0010
$\Delta\kappa_Z$	0.040	0.034	0.036	0.013	0.0016
g^Z_1	0.0038	0.0024	0.0023	0.0007	0.0050







(LO rates, CTEQ5M, k ~ 1.5 expected for these final states)						
Process	*WWW*	*WWZ*	*ZZW*	*ZZZ*	*WWWW*	*WWWZ*
N(m_H = 120 GeV)	2600	1100	36	7	5	0.8
N(m_H = 200GeV)	7100	2000	130	33	20	1.6

pp collisions beyond the LHC

Febr 2014

Design study for Future Circular Colliders

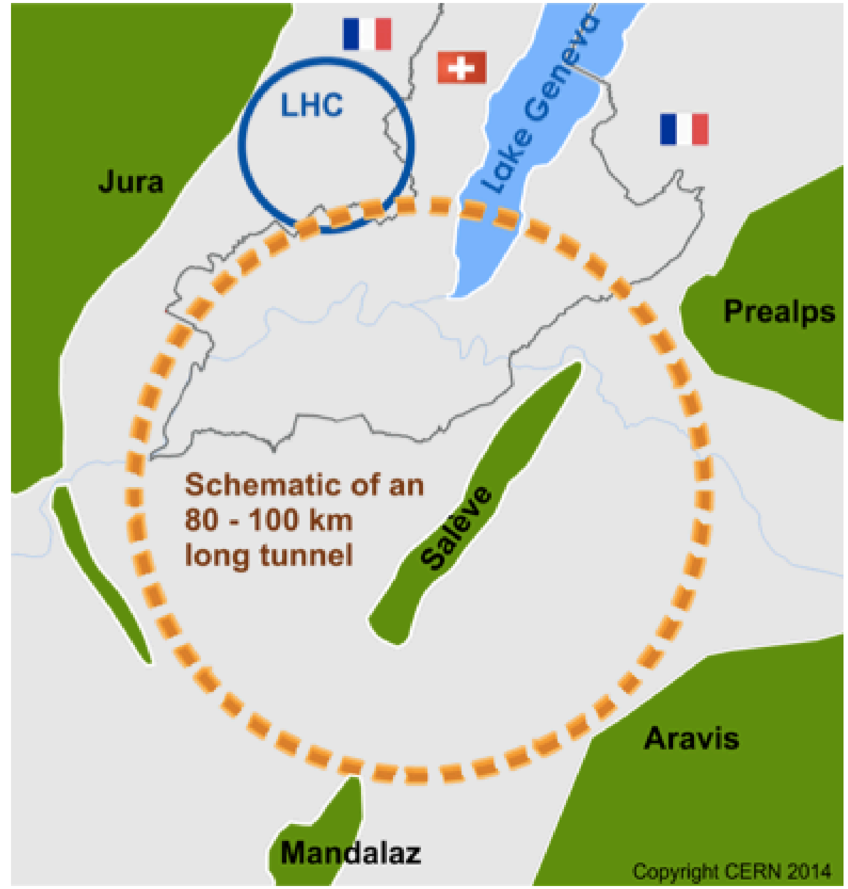
https://espace2013.cern.ch/fcc/

Forming an international collaboration to study:

- *pp*-collider (*FCC-hh*) → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- e^+e^- collider (*FCC-ee*) as potential intermediate step
- *p-e* (*FCC-he*) option
- **80-100 km infrastructure** in Geneva area



M.Benedikt

UNIVERSITÉ DE GENÈVE FCC

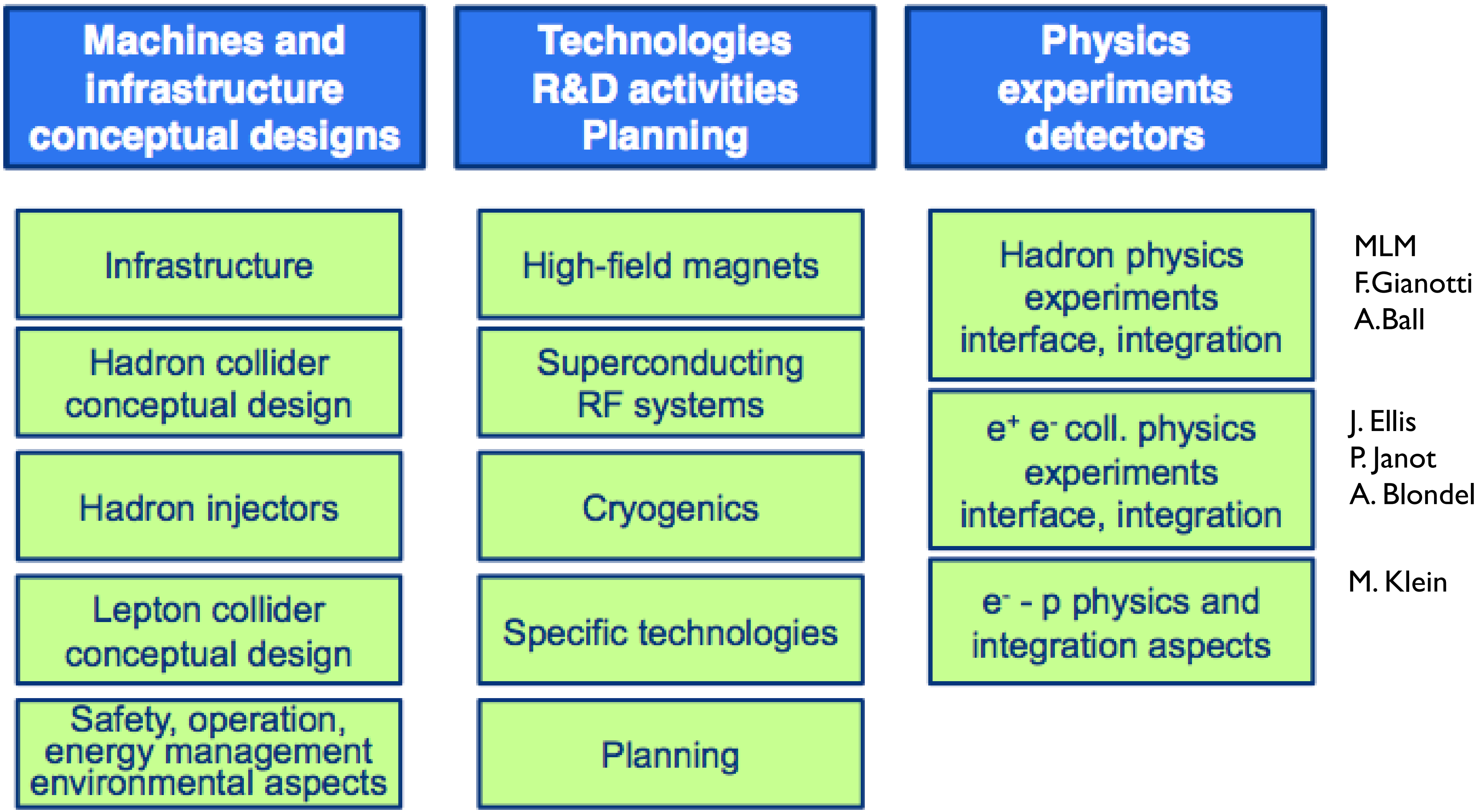
Future Circular Colliders Study Kickoff Meeting

12-15 February 2014
University of Geneva, Geneva
Europe/Zurich timezone

Search

Webcast: Please note that this event will be available live via the Webcast Service.

Future Circular Collider Kickoff Meeting

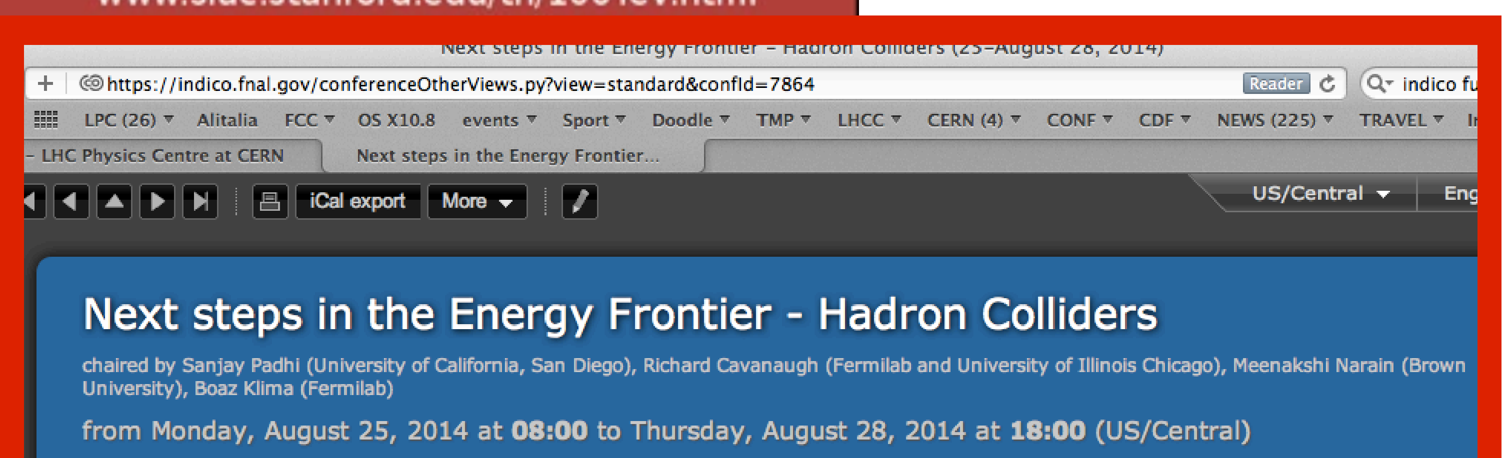


Target: conceptual design report (CDR) ready for the next Strategy Group assessment (~2018)

- **Goal of this effort:** Conceptual design report (CDR) and first cost estimate ready for the next Strategy Group assessment (~2018)
- **Likely next step:** Commission a full technical design report (TDR), ready for the following Strategy Group assessment (~2024)
- **Plausible next step at 2024 Strategy Review:** Review TDR and updated cost estimate, in view of LHC14@300fb^{-1} results and more. Recommend CERN Council to approve, abort, or postpone.

==> we have ~10 years to articulate the physics case, focusing on the physics discussion and on the study of LHC results

Parallel activities in the world



Higgs physics

NLO rates

$$\mathbf{R(E)} = \sigma(\text{E TeV})/\sigma(14\ \text{TeV})$$

	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

In several cases, the gains in terms of "useful" rate are much bigger.
E.g. when we are interested in the large-invariant mass behaviour of the final states:
$\sigma(ttH, p_T^{top} > 500\ \text{GeV}) \Rightarrow R(100) = 250$

Task: explore new opportunities for measurements, to reduce systematics with independent/complementary kinematics, backgrounds, etc.etc.

Examples: how much can we reduce jet veto systematics by "measuring" jet rates/vetoes in "clean" channels like $H \rightarrow ZZ^* / \gamma\gamma$?

Additional Higgs bosons

⇒ commonly present in most SM extensions. E.g. at least 2 H doublets is mandatory in SUSY

⇒ implications for flavour, CPV, EW baryogenesis, ...

Difficult scenarios for searches at LHC:

- suppressed couplings to W/Z
- large masses

⇒ **Problems addressed at 100 TeV thanks to higher rates, higher M reach**

E.g. 2HDM in SUSY

$m_h, m_H, m_A, m_{H^\pm}$ $\tan\beta \equiv \langle\Phi_2\rangle / \langle\Phi_1\rangle$

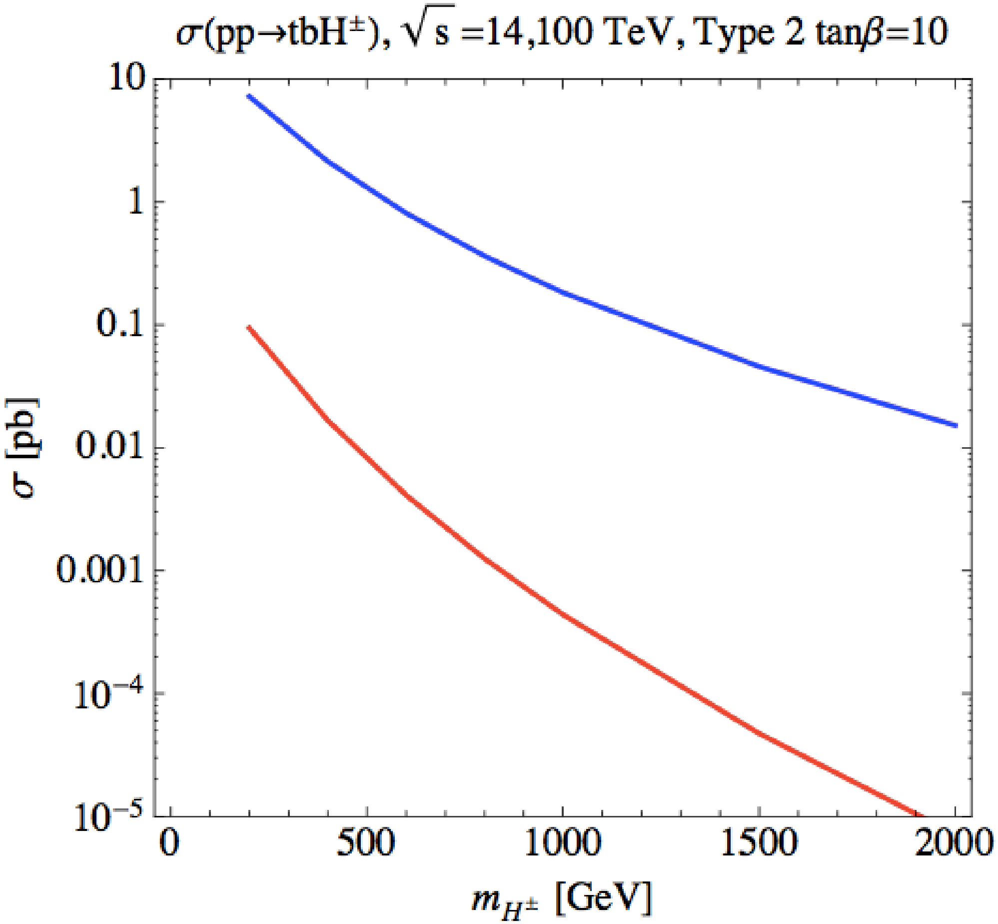
Fine tuning and naturalness: (N.Craig, BSM@100 Wshop)

$$\Delta \approx \sin^2(2\beta)\frac{m_H^2}{m_h^2}$$

$\Delta(\tan\beta = 50) \leq 1 \rightarrow$ $m_H \lesssim 3.1$ TeV

Extra H can be heavy, well above LHC reach, but cannot be arbitrarily heavy

Example: associated $H^{\pm}$ t b production



(N.Craig, BSM@100 Wshop)

Generic features of very heavy H production/decay

Decoupling from W/Z ➡

- "narrow", since $\Gamma \propto m_H$ (cfr $\Gamma \propto m_H^3$ when decaying to W/Z)
- H/A → hh, tt dominate (boosted regime)

WIMP DM search

Can a 100 TeV collider detect or rule out WIMP scenarios for DM ?

<u>DM overclosure upper limits:</u>

M_{WIMP} < 1.8 TeV (g^2/0.3) ⇒

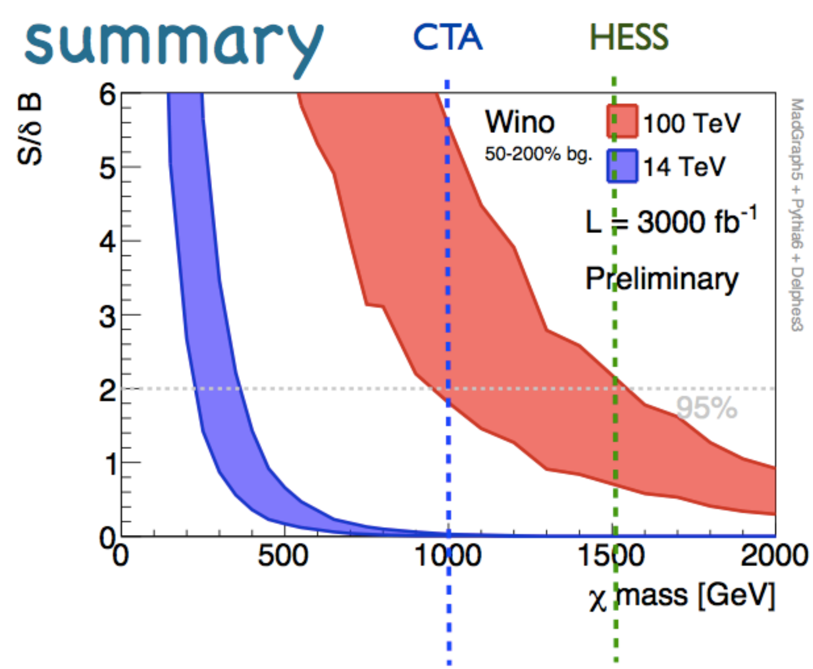
wino: m≲3 TeV

higgsino: m≲1.1 TeV

In anomaly-mediated SUSY or split SUSY ⇒

m_{gluino} ≲ 10 TeV

Wino summary

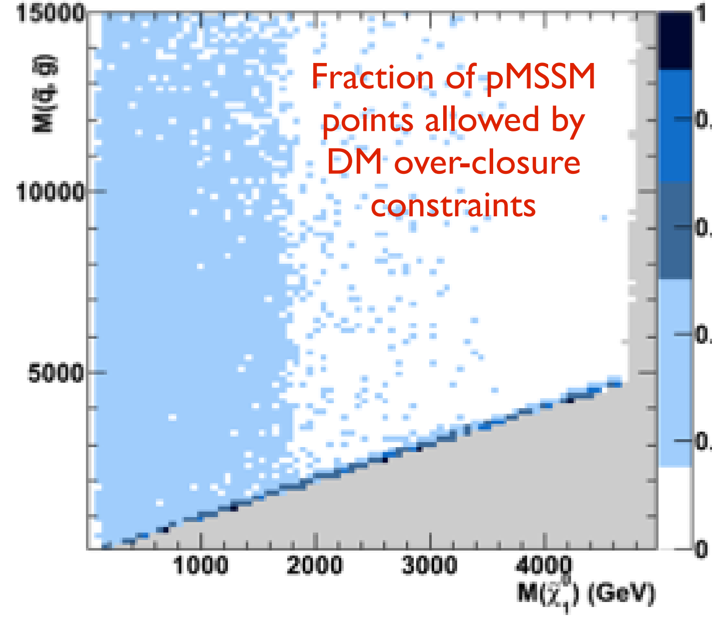


- Main decay mode $\chi^\pm \to \pi^\pm + \chi^0$
- Charge track ≈ 10(s) cm
- In combination with indirect detection, there is hope to "completely cover" the wino parameter space.

L.T.Wang, (see also P.Schwaller and T.Cohen) BSM@100 TeV Workshop

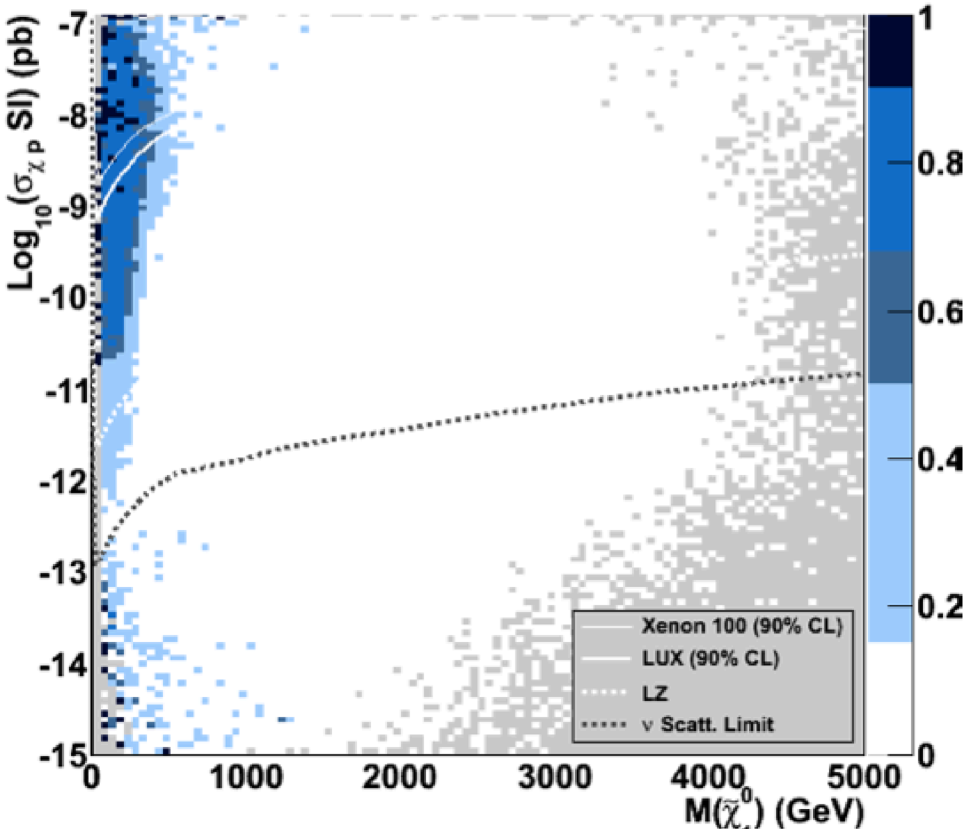
Coverage of pMSSM parameter space using DM constraints and direct searches at 14 and 100 TeV

Arbey, **Battaglia**, Mahmoudi

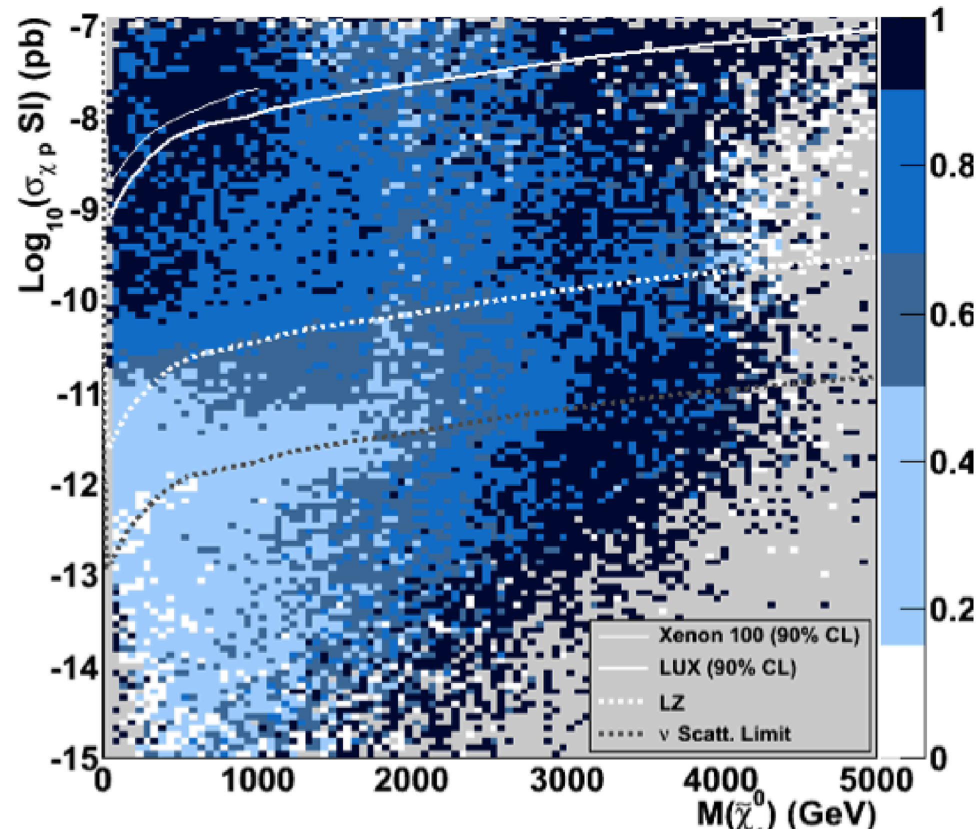


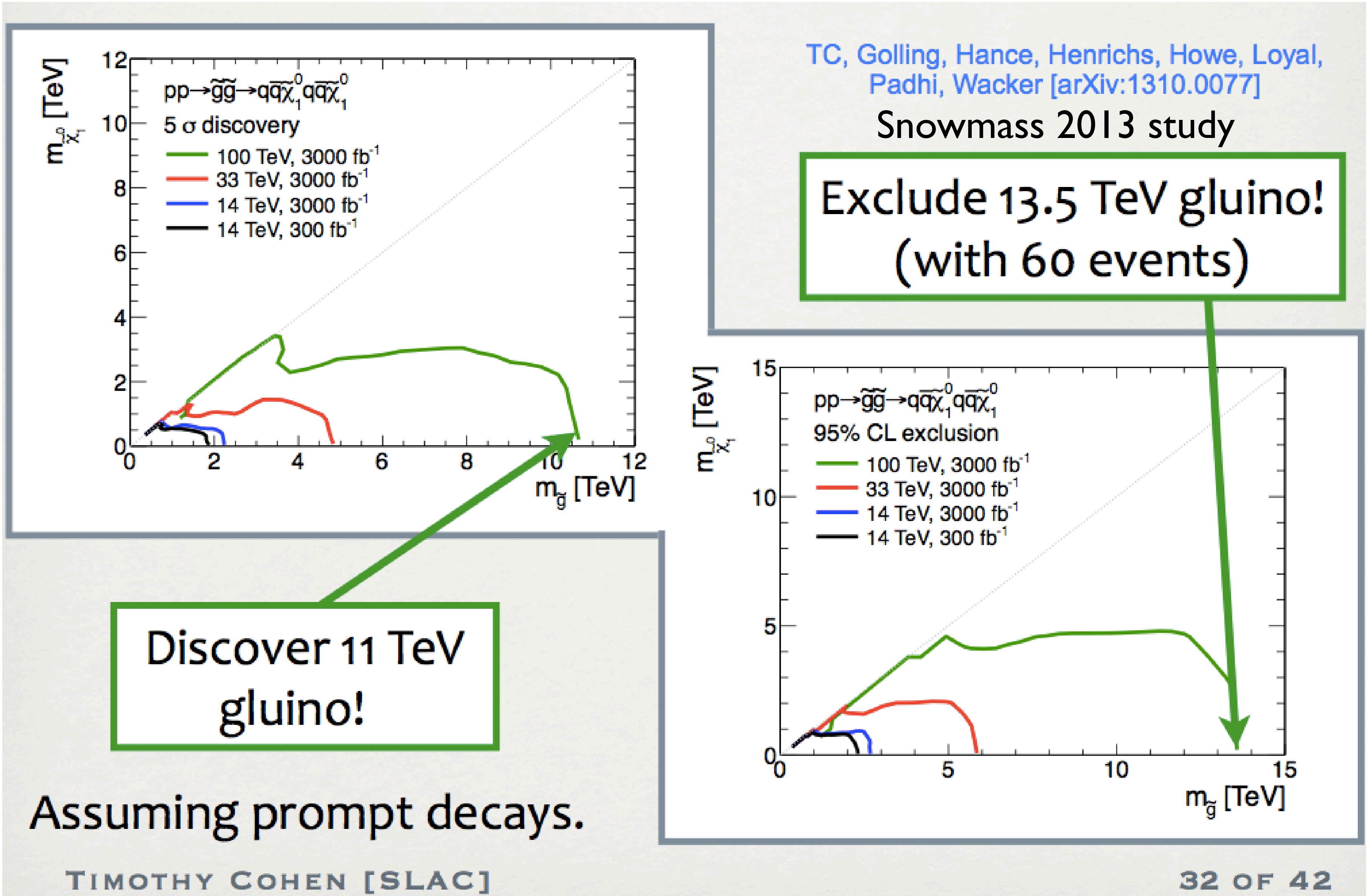
Fraction of pMSSM points that can be excluded at LHC-14 and 100 TeV:

14 TeV



100 TeV





T.Cohen, BSM@100 TeV Workshop,
http://indico.cern.ch/event/284800/

Production and study of SM particles and processes

Improving knowledge of SM interactions contributes to improving sensitivity to BSM searches

The continued exploration of the properties of SM interactions, both in the EW and QCD sector, remains a goal of any future facility, and provides benchmarks for the performance and optimization of the experiments

Example: FCC-ee

J.Ellis

Quantity	Physics	Present precision		TLEP Stat errors	Possible TLEP Syst. Errors	TLEP key	Challenge
M_z (keV)	Input	91187500 ±2100	Z Line shape scan	5 keV	<100 keV	E_cal	QED corrections
Γ_z (keV)	$\Delta\rho$ (T) (no $\Delta\alpha$!)	2495200 ±2300	Z Line shape scan	8 keV	<100 keV	E_cal	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.0001	<0.001	Statistics	QED corrections
N_ν	PMNS Unitarity sterile ν's	2.984 ±0.008	Z Peak	0.00008	<0.004		Bhabha scat.
N_ν	PMNS Unitarity sterile ν's	2.92 ±0.05	(γ+Z_inv) (γ+Z→ ℓℓ)	0.001 (161 GeV)	<0.001	Statistics	
R_b	δ_b	0.21629 ±0.00066	Z Peak	0.000003	<0.000060	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho, \varepsilon_3, \Delta\alpha$ (T, S)	0.1514 ±0.0022	Z peak, polarized	0.000015	<0.000015	4 bunch scheme, > 2exp	Design experiment
M_W MeV/c2	$\Delta\rho, \varepsilon_3, \varepsilon_2, \Delta\alpha$ (T, S, U)	80385 ± 15	Threshold (161 GeV)	0.3 MeV	<0.5 MeV	E_cal & Statistics	QED corections
m_{top} MeV/c2	Input	173200 ± 900	Threshold scan	10 MeV	<10MeV	E_cal & Statistics	Theory interpretation 40 MeV?

http://CERN.CH/tlep

TLEP/FCC-ee Physics Report: http://arxiv.org/abs/arXiv:1308.6176

Example: FCC-eh

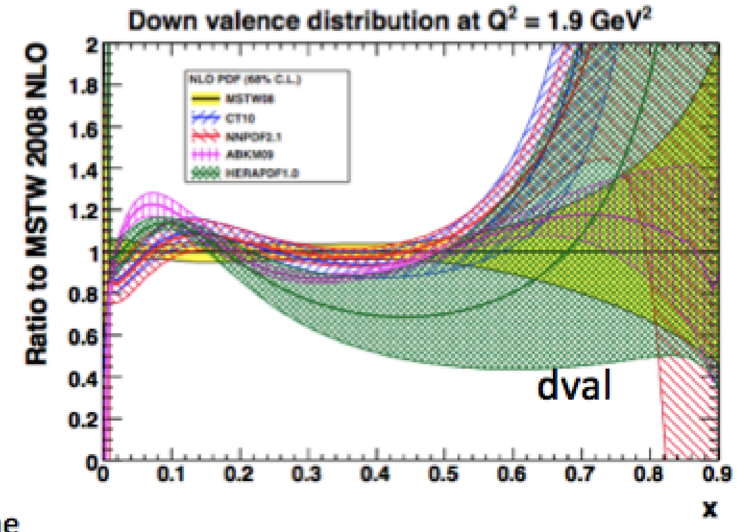
M.Klein

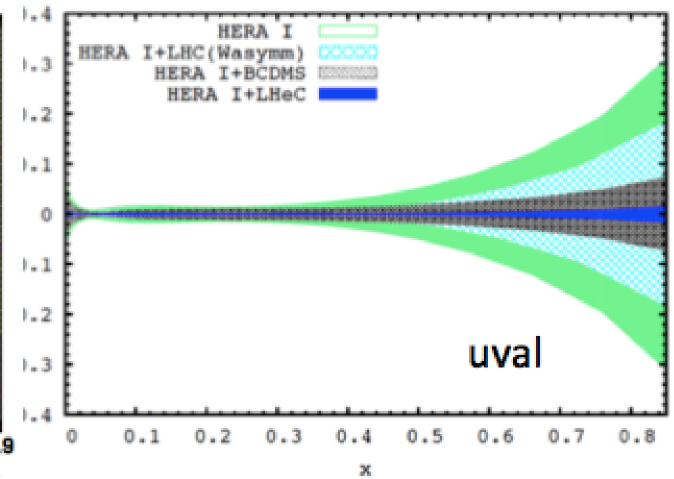
Valence quark distributions

Now… | …Then

Current knowledge is limited at high x:

- Lumi barrier
- challenging systematic
- nuclear effects
- Effects of higher twists

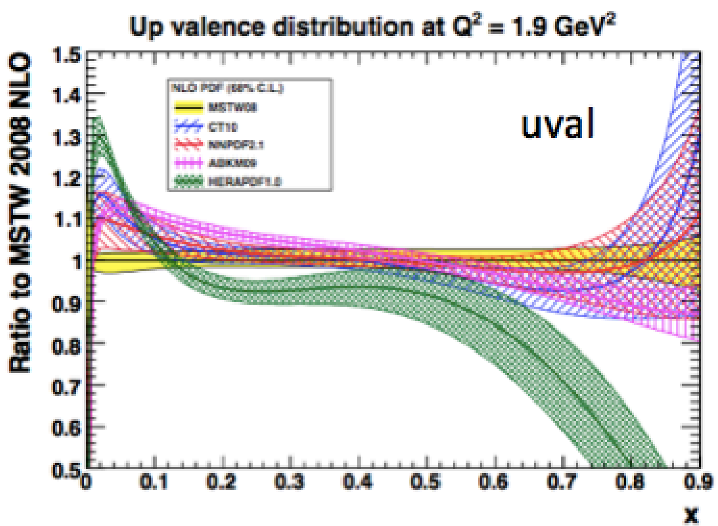


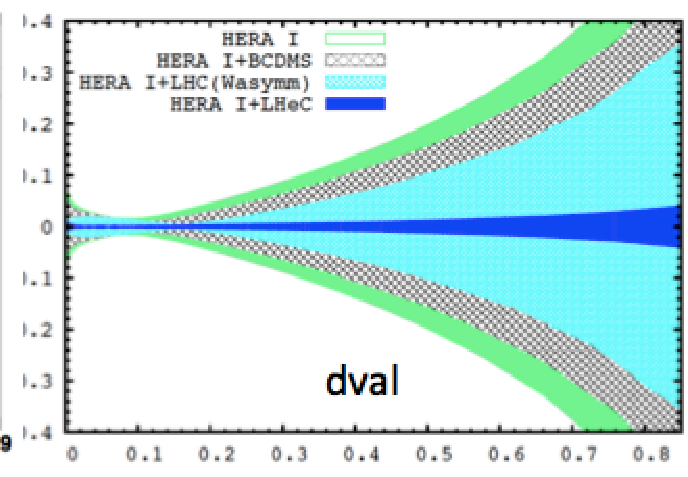


LHeC could improve the knowledge of the valence at high x to a precision of:

- 2% (uval) x=0.8
- 4% (dval) x=0.8

Important for d/u limit clarification





http://CERN.CH/lhec

LHeC Physics Report: http://arxiv.org/abs/arXiv:1206.2913

$10\ ab^{-1}$ at 100 TeV imply:

10^{10} Higgs bosons => 10^4 x today

⇒ precision measurements

⇒ rare decays, FCNC probes

($H \to e\mu$, $t \to cV$ ($V=Z,g,\gamma$), $t \to cH$, ...)

⇒ CP violation

10^{12} top quarks => 5 10^4 x today

=> 10^{12} W bosons from top decays

=> 10^{12} b hadrons from top decays (particle/antiparticle tagged)

=> 10^{11} $t \to W \to$ taus ⇒ rare decays $\tau \to 3\mu$, $\mu\gamma$, CPV

=> few x10^{11} $t \to W \to$ charm hadrons

⇒ rare decays $D \to \mu^+\mu^-$, ..., CPV

The possibility of detectors dedicated to final states in the 0.1 - 1 TeV region deserves very serious thinking:

focus on Higgs, DM and weakly interacting new particles, top, W

W decays

- W mass ??
- SM rare decays -- Examples:

$W^\pm \to \pi^\pm \gamma$ $\qquad BR_{SM} \sim 10^{-9}$, CDF $\leq 6.4 \times 10^{-5}$

$W^\pm \to D_s^\pm \gamma$ $\qquad BR_{SM} \sim 10^{-9}$, CDF $\leq 1.2 \times 10^{-2}$

What is the theoretical interest in measuring these rates? What else ?

- SM inclusive decays -- Examples:

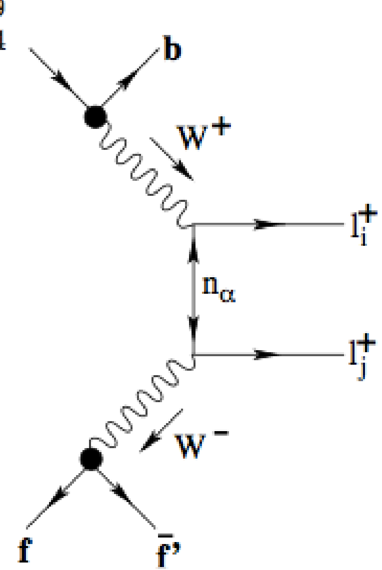
$R = BR_{had} / BR_{lept}$: what do we learn ? Achievable precision for CKM, α_S , ... ?

- BSM decays -- Are there interesting channels to consider? -- Example

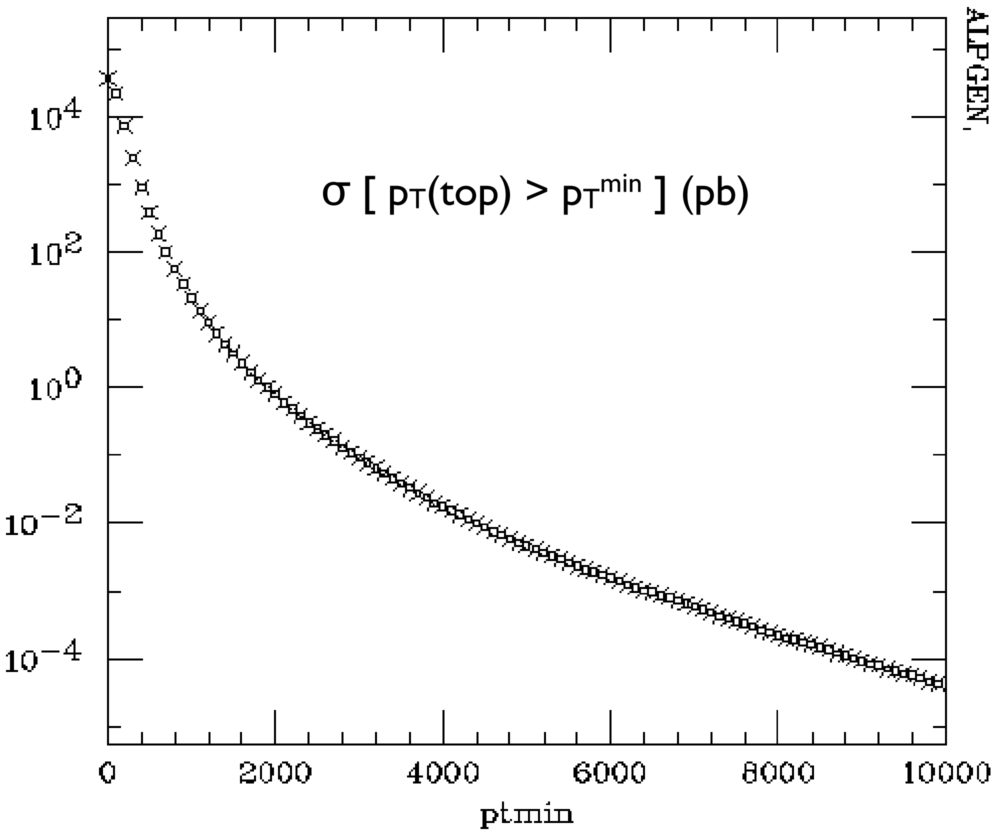
BNL-HET-06/9
OITS-784

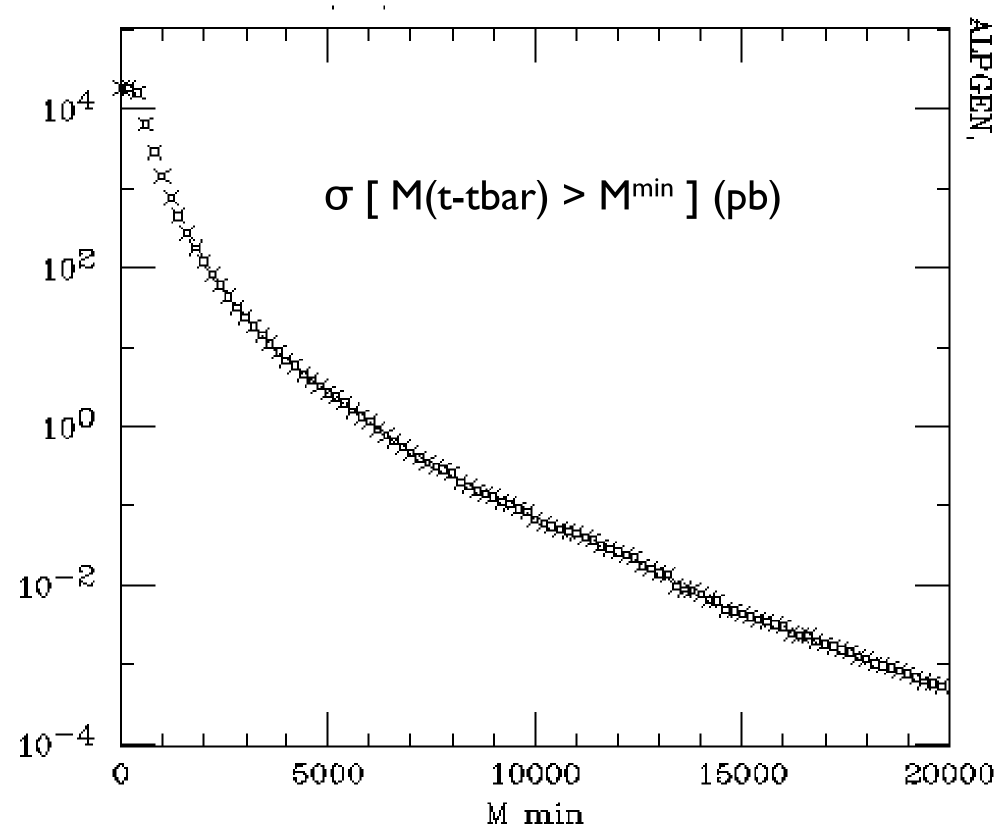
Majorana neutrinos and lepton-number-violating signals in top-quark and W-boson rare decays

Shaouly Bar-Shalom[a,*] Nilendra G. Deshpande[b,†] Gad Eilam[a,‡] Jing Jiang[b,§] and Amarjit Soni[c,¶]



Inclusive t-tbar production: distributions





Tasks:

o explore tagging of multi-TeV tops

o study mass resolution for resonance searches, define search potential (σ_{BSM} vs M_{BSM})

o explore opportunities for top coupling studies at large Q

Example: what can we learn from
10^4 pp → W* → top+ bottom with M(tb) > 7 TeV ?

Probing top couplings

JA Aguilar-Saavedra

Weak moments: the contenders

Wtb $-\frac{g}{\sqrt{2}}\bar{b}_L \frac{i\sigma^{\mu\nu}q_\nu}{M_W} g_R \, t_R W_\mu^-$

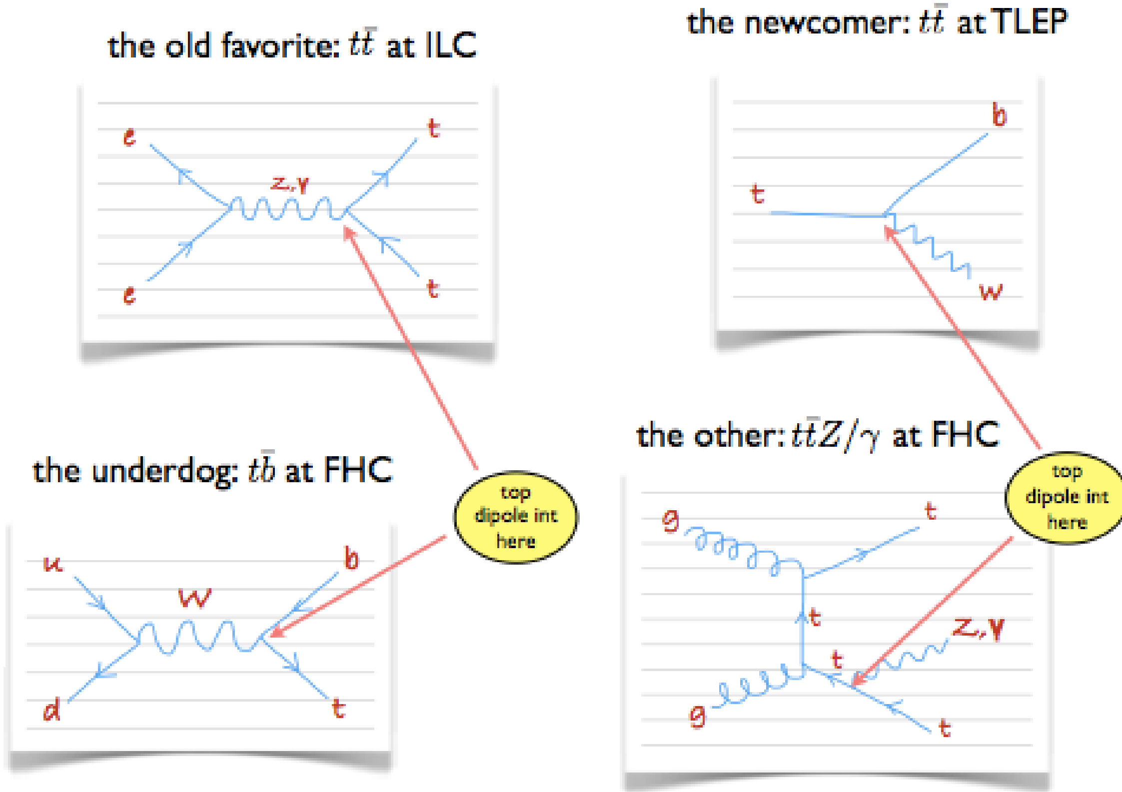
Ztt $-\frac{g}{2c_W}\bar{t}\frac{i\sigma^{\mu\nu}q_\nu}{M_Z} d_V^Z \, t Z_\mu$

$\sqrt{2} C_{uW}^{33} \frac{v^2}{\Lambda^2}$

$\sqrt{2} c_W \, \mathrm{Re}\, C_{uW}^{33} \frac{v^2}{\Lambda^2} + \text{other}$

$\frac{\sqrt{2}}{e} s_W \, \mathrm{Re}\, C_{uW}^{33} \frac{v m_t}{\Lambda^2} + \text{other}$

γtt $-e\bar{t}\frac{i\sigma^{\mu\nu}q_\nu}{m_t} d_V^\gamma \, t A_\mu$



Projected sensitivity reach:

ILC $\mathrm{Re}\, C_{uW}^{33}/\Lambda^2 \in [-0.128, 0.140]\ \mathrm{TeV}^{-2}$ 95% CL $\Lambda > 2.7\sqrt{\mathrm{Re}\, C}\ \mathrm{TeV}$

FCC-ee $\mathrm{Re}\, C_{uW}^{33}/\Lambda^2 \in [-0.083, 0.083]\ \mathrm{TeV}^{-2}$ 95% CL $\Lambda > 3.5\sqrt{\mathrm{Re}\, C}\ \mathrm{TeV}$

FCC-hh $\mathrm{Re}\, C_{uW}^{33}/\Lambda^2 \in [-0.043, 0.046]\ \mathrm{TeV}^{-2}$ 95% CL $\Lambda > 4.7\sqrt{C}\ \mathrm{TeV}$

Concluding remarks

- **LHC measurements of SM phenomena moved to a new phase of quantitative and precision level**
- **It's a great reward for theorists to see the fruits of years of work developing tools**
    - theory/data agreement beyond expectations and hopes
    - thanks to the expt's for the thorough and incisive tests of theory
    - still, interesting open issues and problems to keep the challenge up
- **The Higgs is there ... but where is everyone else ??**
- **The LHC physics programme is immensely broad and diversified**
- **While the search for BSM physics and the precision study of EWSB remain the main goals, greatly valuable information about SM dynamics is emerging from the data**
- **The 100 TeV collider is far away, but offers the richest prospects for the long-term future of HEP**