Experimental Overview

ICFA Seminar, CERN, 3rd October 2011

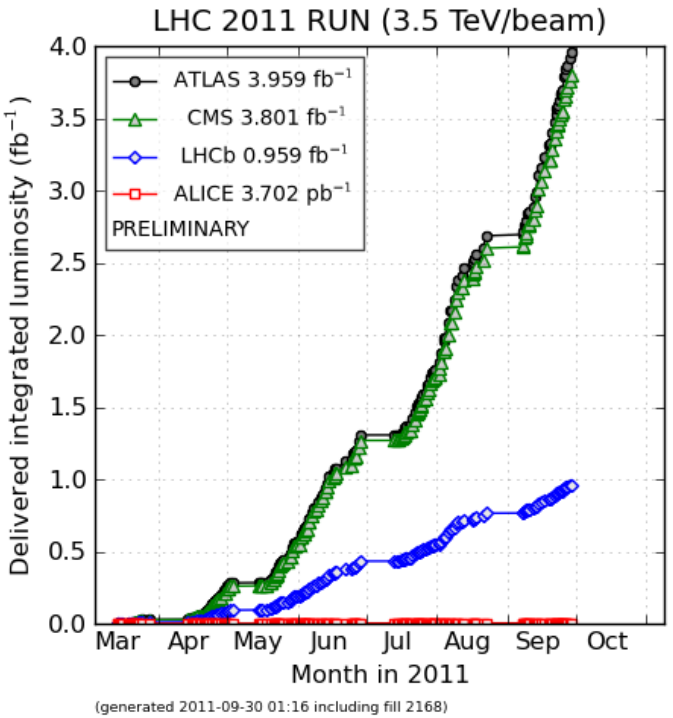
Terry Wyatt.
University of Manchester.

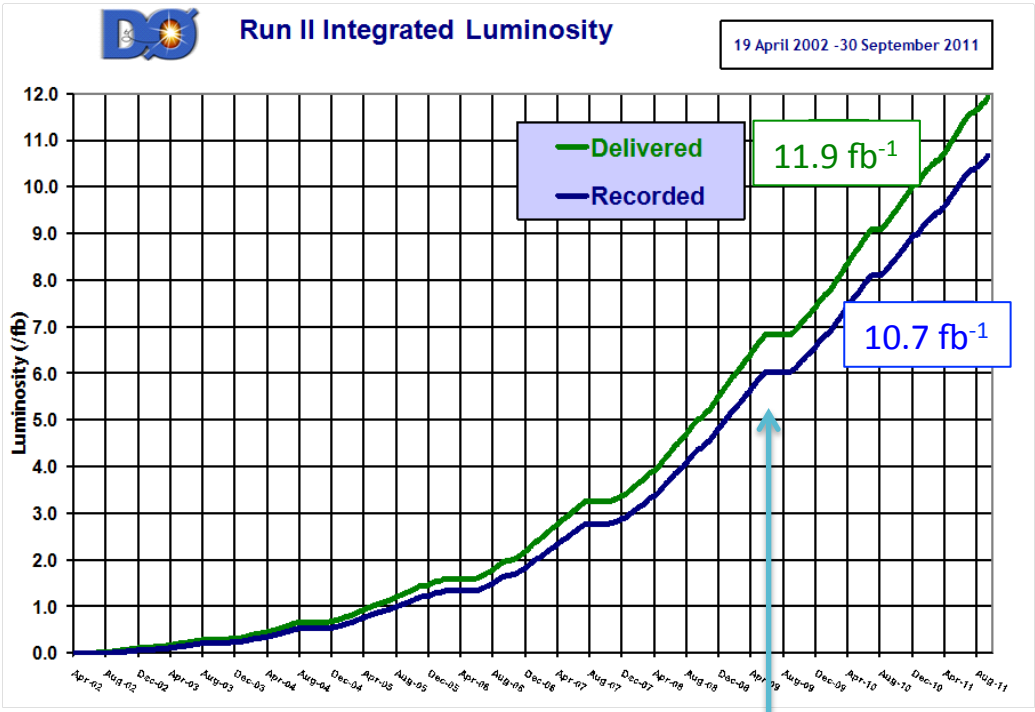
Overview of the Overview

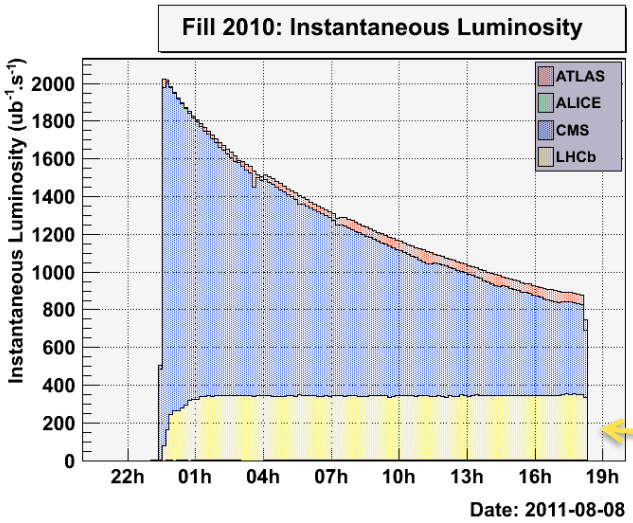
- Heavy Quarks (top, b, c)
- EW & QCD
- Higgs
- BSM searches
- Heavy ions
- Neutrinos

With thanks to all the speakers at LP11, whom I have liberally plagiarized

2011: a great year for colliders!

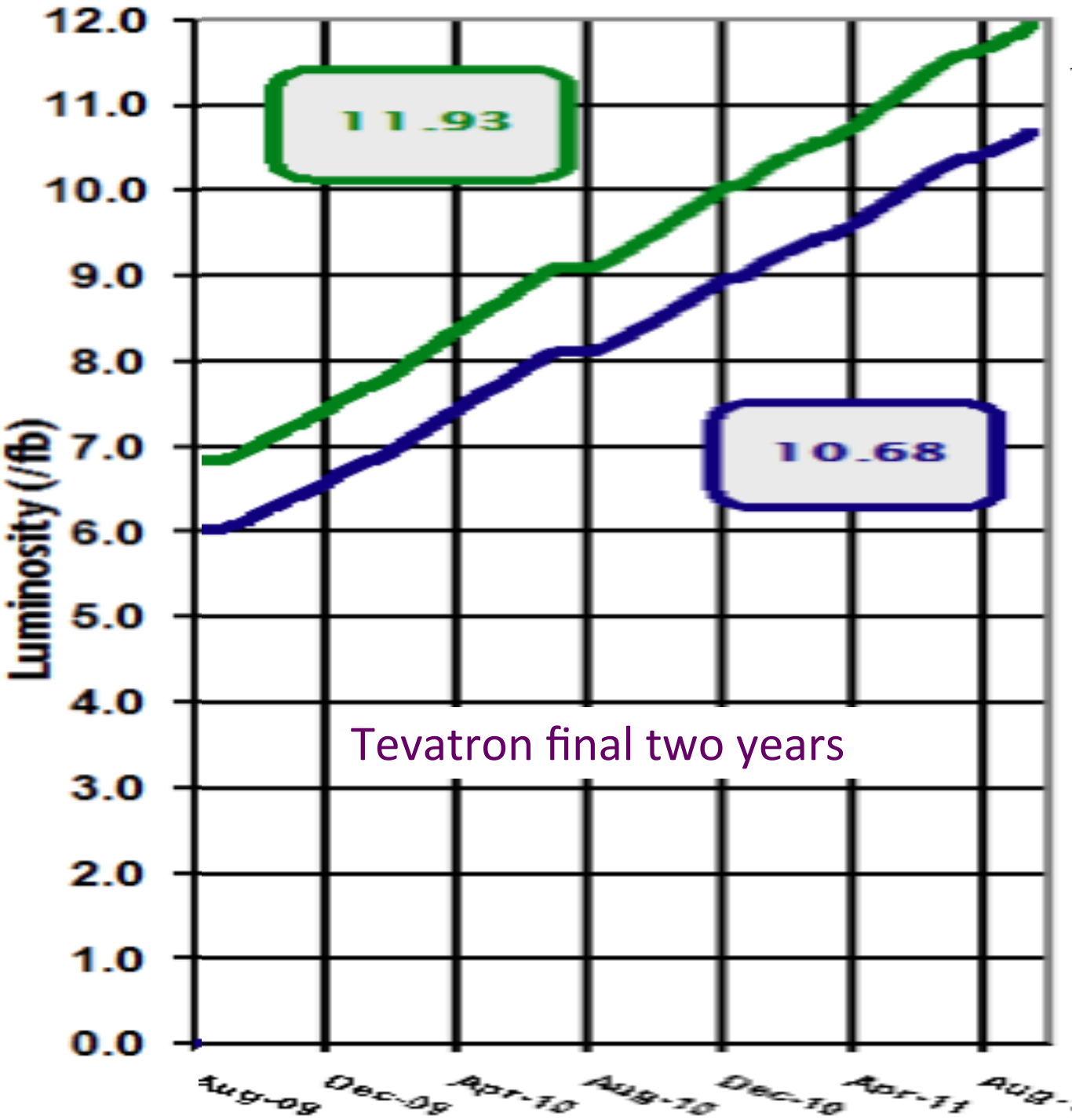


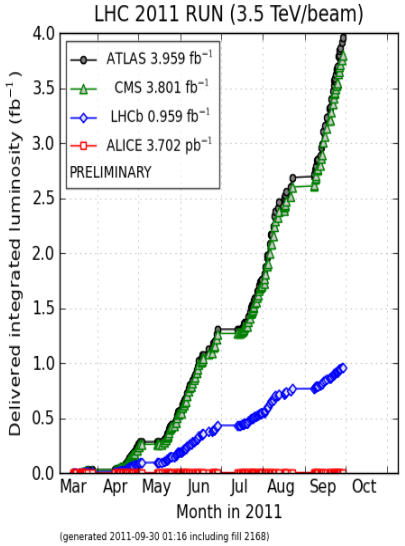




- But also a poignant year
  - Final data taking summary from Tevatron
- Data taking efficiencies > 90% for most experiments
- Phenomenal speed from data taking to physics results!
- LHC aperture, emittance, reproducibility, beam instrumentation, agreement with simulations
  - ➔ long term prospects look excellent

Auto luminosity leveling for LHCb at $\langle\mu\rangle \approx 1.5$





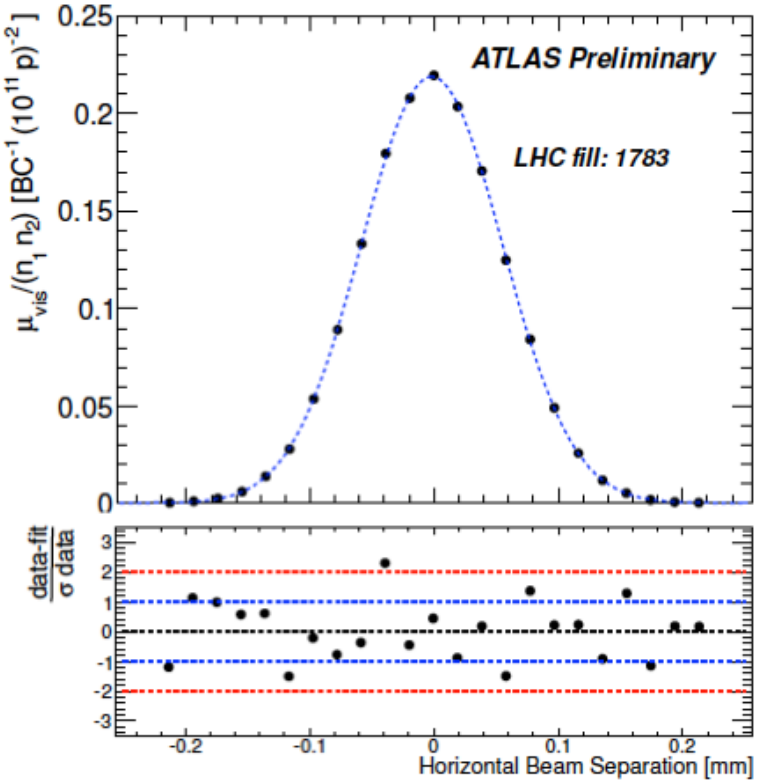
[Passing the baton:](#)

Tevatron and LHC on the same horizontal and vertical scales!

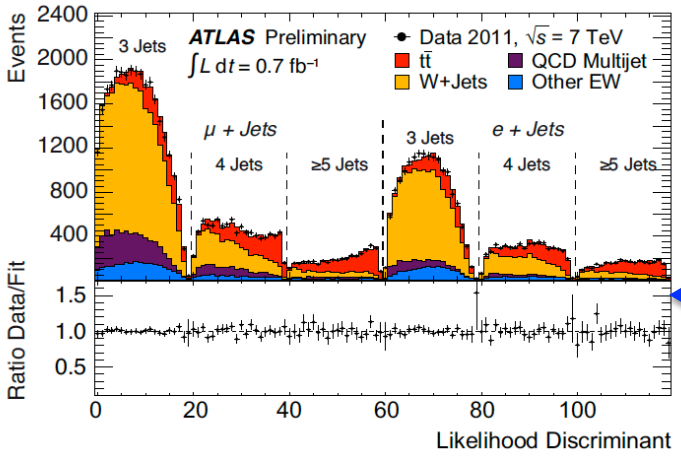
LHC luminosity determination

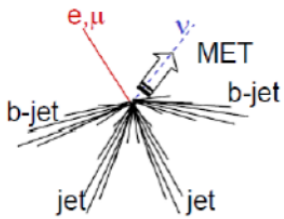
$$\mathcal{L} = \frac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

- Calibrated using van der Meer scans
- Present uncertainty ±3.7%
  - dominated by beam current measurements ±3%
    - already impressive
    - could come down by around a factor of two?

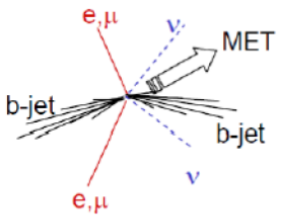


Top pair cross section

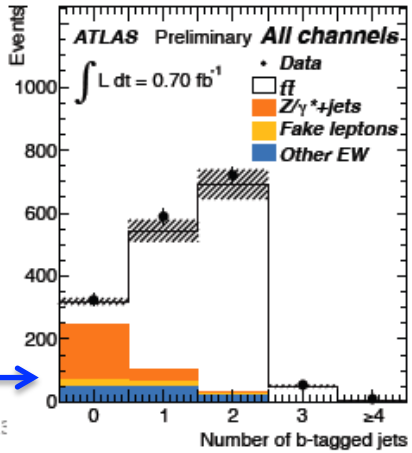




lepton + jets

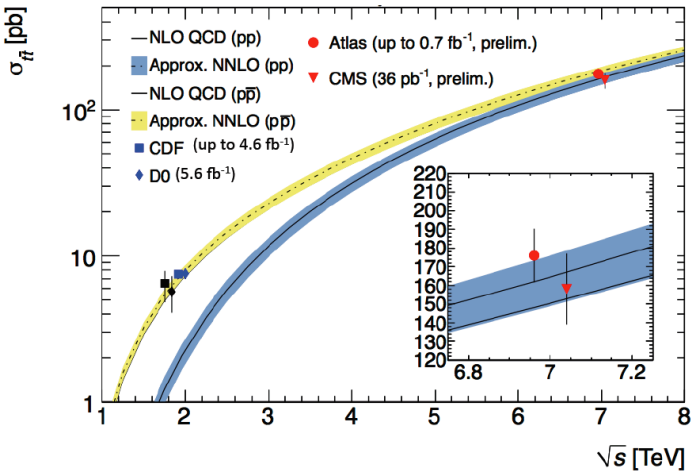


dileptons



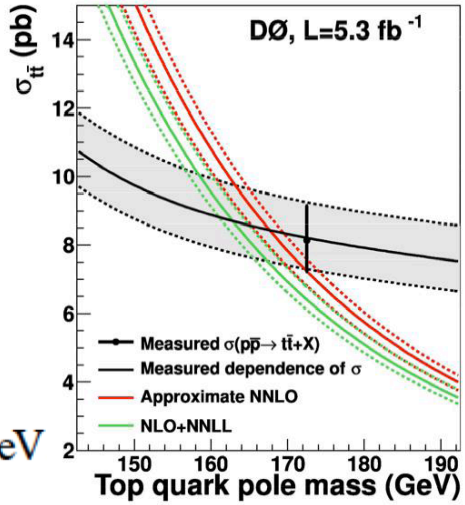
tt production cross section

precision 7-10% at both Tevatron and LHC

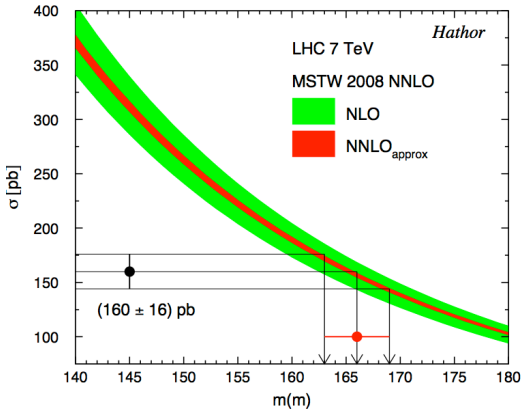


Extract pole mass

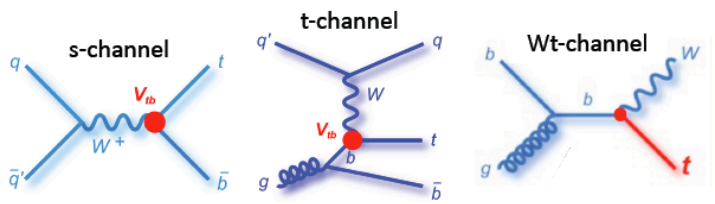
(complementary systematictics to direct reconstruction)



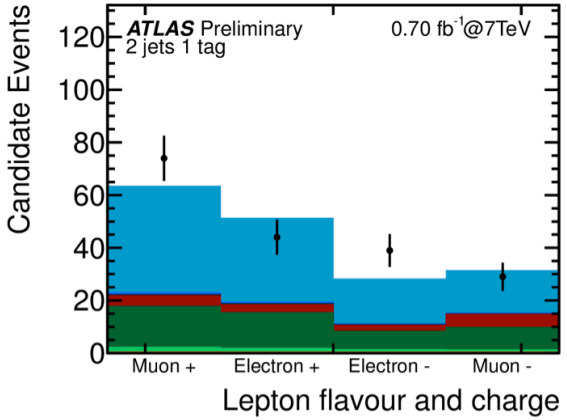
$$m_{\text{top}}^{\text{pole}} = (166.4\,^{+7.8}_{-7.3})\ \text{GeV}$$



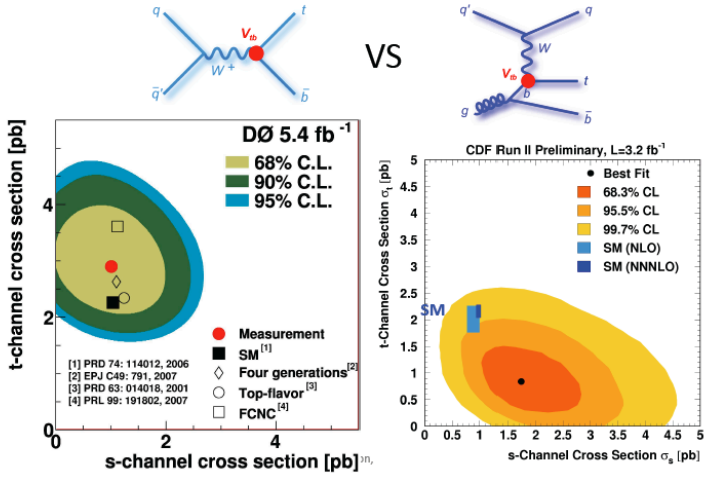
Electroweak production of single top

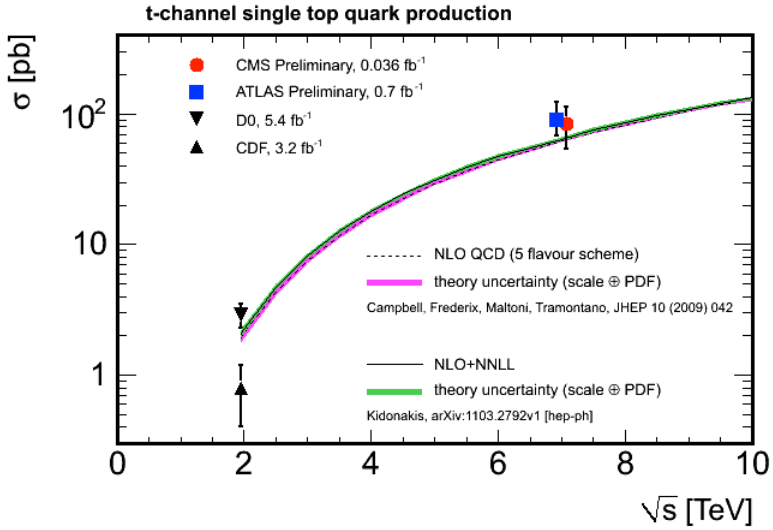


For M_t = 172.5 GeV	σ_{tb}	σ_{tqb}	σ_{tW}
$p\bar{p}$ @ 1.96 TeV	1.04 ± 0.04 pb	2.26 ± 0.12 pb	0.28 ± 0.06 pb
pp @ 7 TeV	4.6 ± 0.3 pb	64.6 +3.3 -2.6 pb	15.7 ± 1.4 pb



Try to distinguish s and t channel production

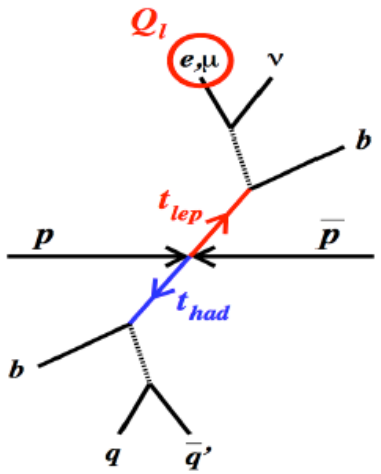


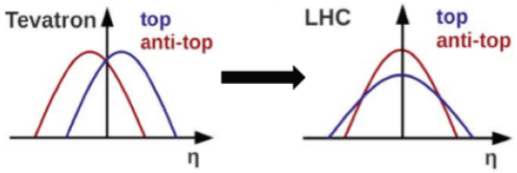


σ_{tqb} (pb) for $m_t = 172.5$ GeV:

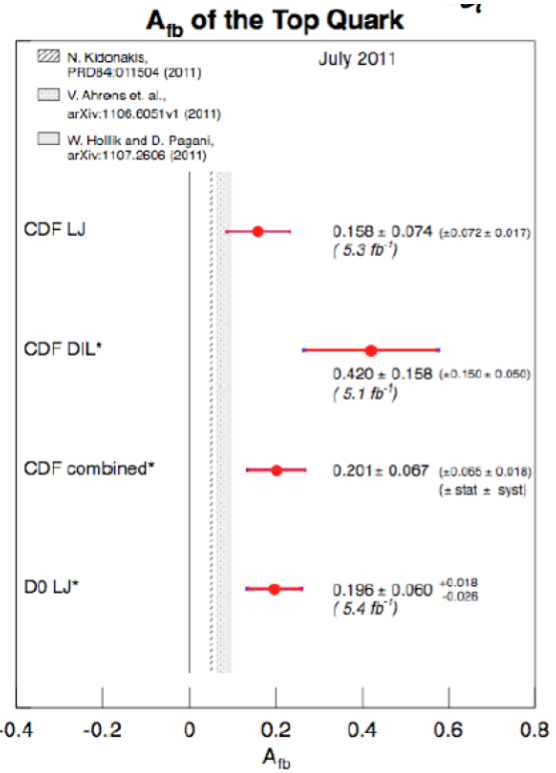
CDF (3.2 fb^{-1})	0.8 ± 0.4	
D0 (5.4 fb^{-1}, arXiv:1105.2788)	2.90 ± 0.59	5.5σ
CMS (36 pb^{-1}, arXiv:1106.3052)	$83.6 \pm 29.8(\text{stat} + \text{syst}) \pm 3.3(\text{lumi})$	3.7σ
Atlas (0.7 fb^{-1})	90^{+32}_{-22}	7.6σ

Top forward-backward asymmetry

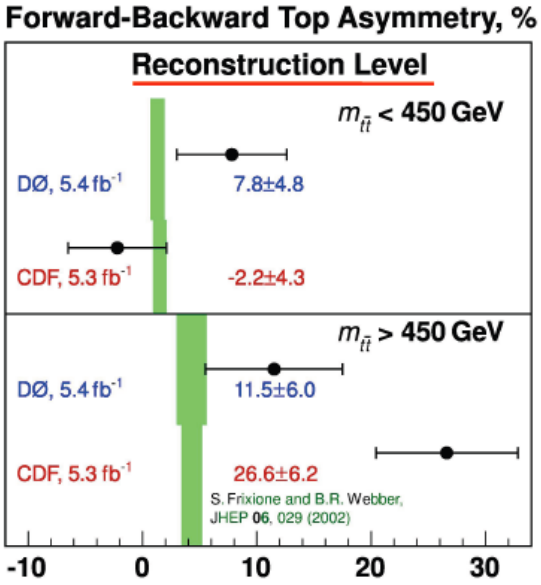


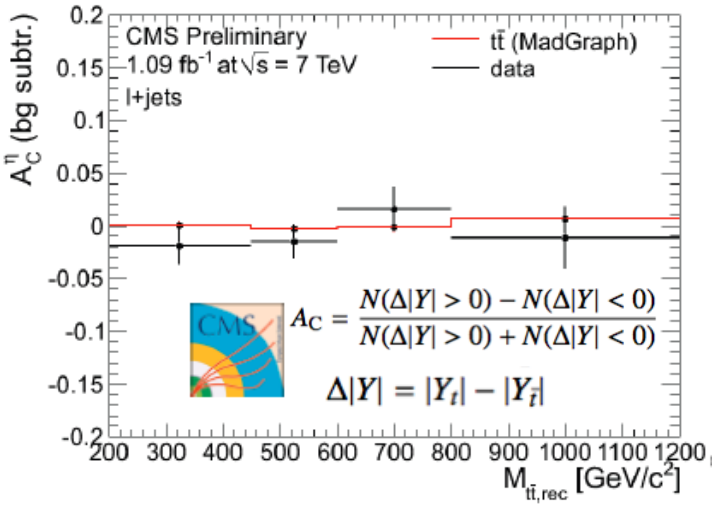


- Asymmetry of 5.8±0.75% expected at Tevatron, much smaller at LHC
  - CDF and D0 see larger effect at ~2.4 σ
    more to come from 10 fb^{-1} sample
  - CMS: A^{η}=-1.6±3.0(stat)$^{+1.0}_{-1.9}$(syst)%
    ATLAS: A^{η}=-2.4±1.6(stat)±2.3(syst)%
    Theory: A^{η}=1.3%



- CDF sees mass dependence
  - not confirmed by DØ

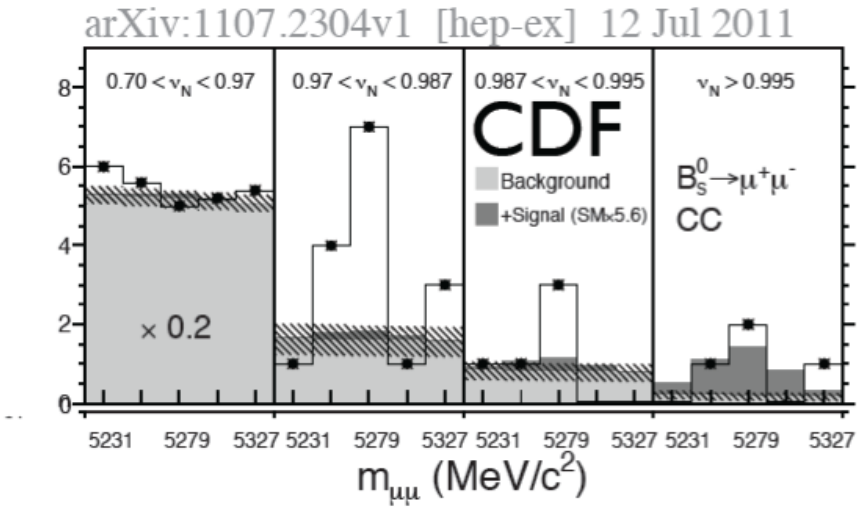




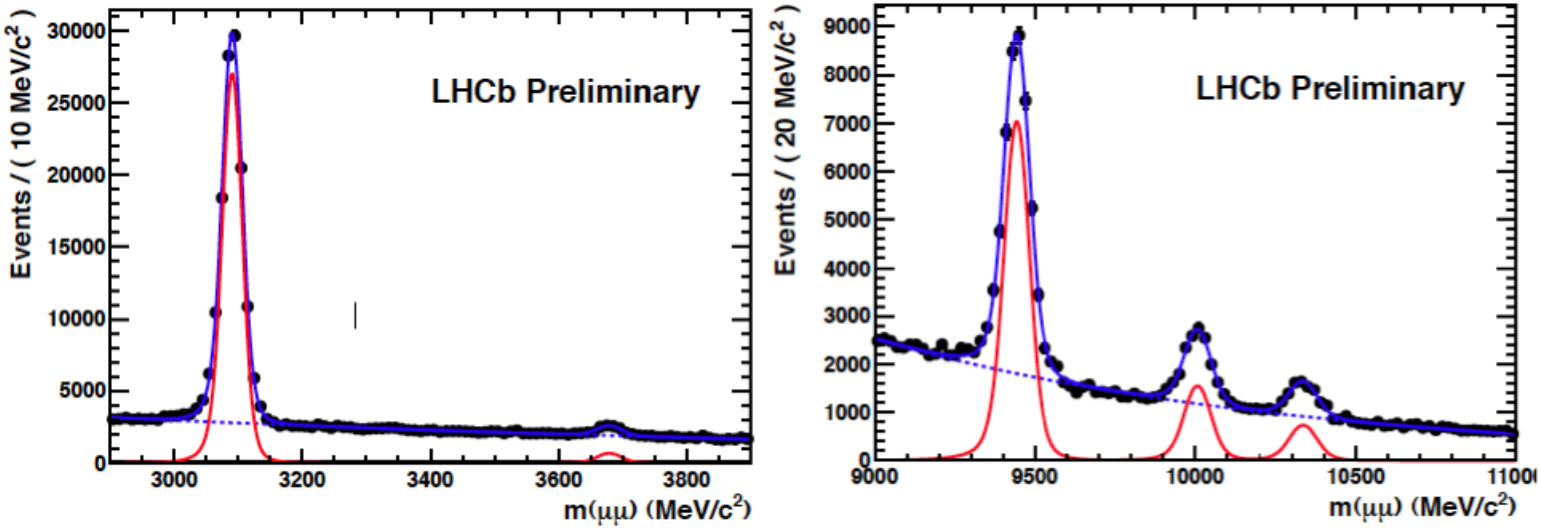
Search for $B_s \rightarrow \mu\mu$

CDF recently reported a hint of signal:

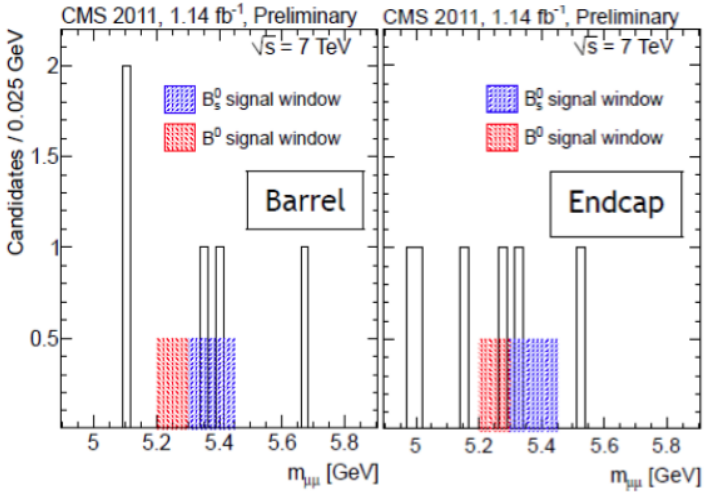
- p-value background only: 0.3%
- p-value background + SM Br: 1.9%
- $Br_{CDF}(B_s \rightarrow \mu\mu) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$

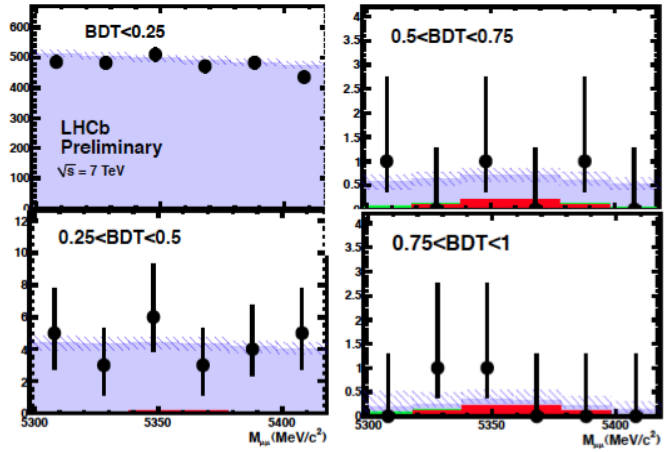


- LHCb: calibrate mass scale and resolution with J/ψ and ϒ

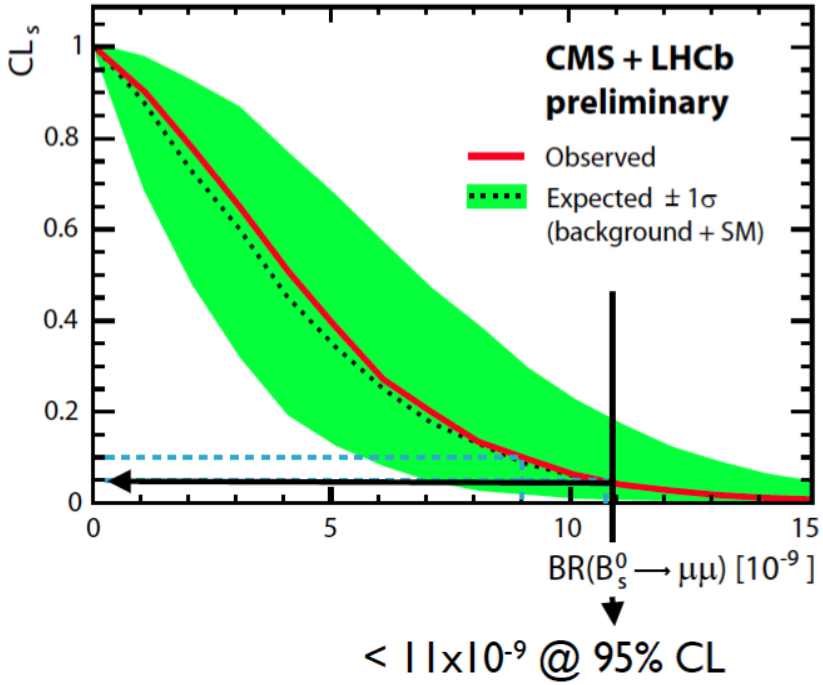


CMS+LHC*b*: Combined $B_s \to \mu\mu$ Limit



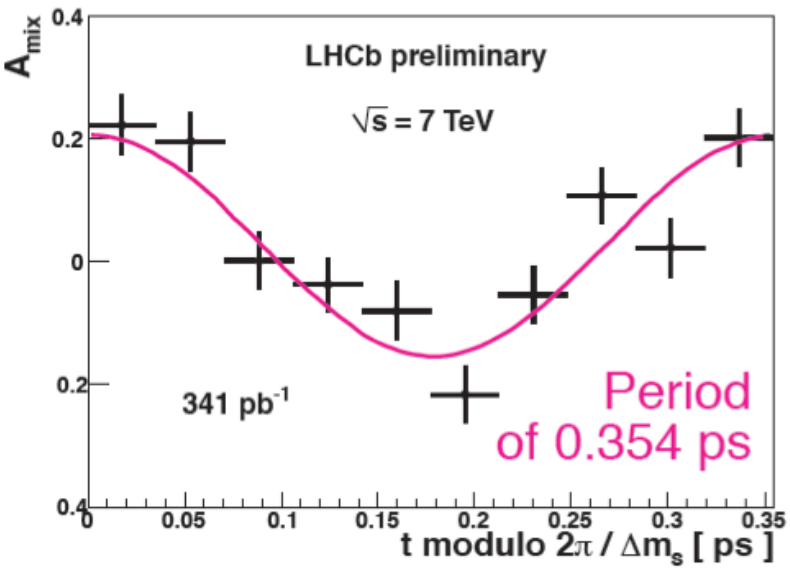


- Use $(f_s/f_d)_{LHCb} = 0.267^{+0.021}_{-0.020}$
- p-value background only: 8%
- p-value background + SM BR: 55%
- $Br(B_s \to \mu\mu) < 11 \times 10^{-9}$ @ 95% CL
- Given that the 95% CL is still 3.4 x SM, there remains plenty of room for NP, keep an eye in the near future!

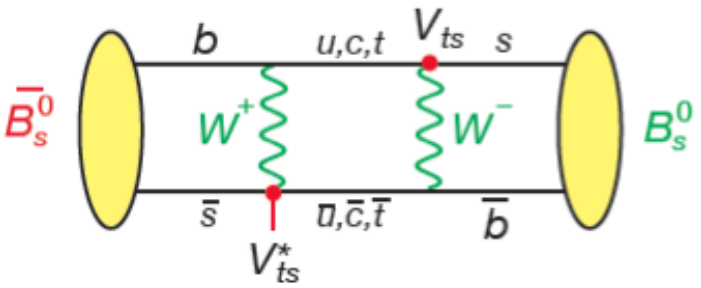


< 11x10^{-9} @ 95% CL

B_s mixing



Opposite-side & same-side flavor-tagging



- Δm_s (world average) = 17.731 ± 0.045 ps^{-1}
  - Dominated by LHCb with 341 pb^{-1}
- Δm_s (Standard Model) = 16.8 +0.26 -0.15 ps^{-1}

CP violation in neutral B meson semileptonic decays

Direct semileptonic decay

Neutral *B* meson oscillation and then semileptonic decay

Measure *CP* violation in mixing via

$$A^b_{sl} = \frac{N_b(\mu^+\mu^+) - N_b(\mu^-\mu^-)}{N_b(\mu^+\mu^+) + N_b(\mu^-\mu^-)}$$

- Dominant systematics controlled by:
  - reversing field directions
  - measuring difference in $K^{\pm} \rightarrow \mu^{\pm}$ rates in data

Asymmetry is a linear combination semileptonic charge asymmetries of B^0_d and B^0_s

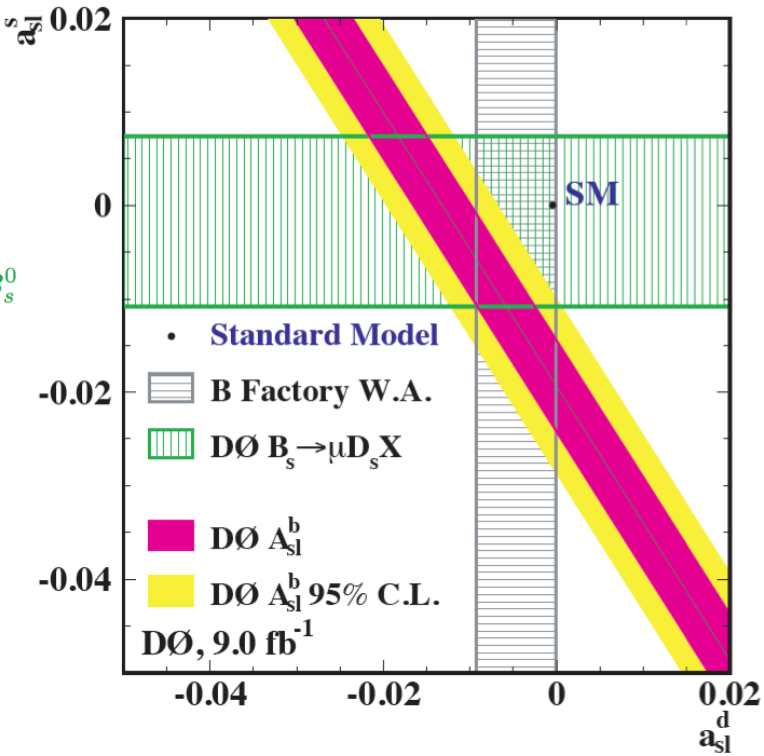
$$A^b_{sl} = C_d a^d_{sl} + C_s a^s_{sl} \; ; \qquad a^b_{sl} = \frac{\Gamma(\overline{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(\overline{B} \to \mu^+ X) + \Gamma(B \to \mu^- X)}$$

Coefficients depend on mean mixing probability and production fractions

DØ Update 9.0 fb^{-1}

$$A^b_{sl} = (-0.787 \pm 0.172 \pm 0.093)\%$$

Now a 3.9σ deviation from SM prediction



CP violation in neutral B meson semileptonic decays

Direct semileptonic decay

Neutral *B* meson oscillation and then semileptonic decay

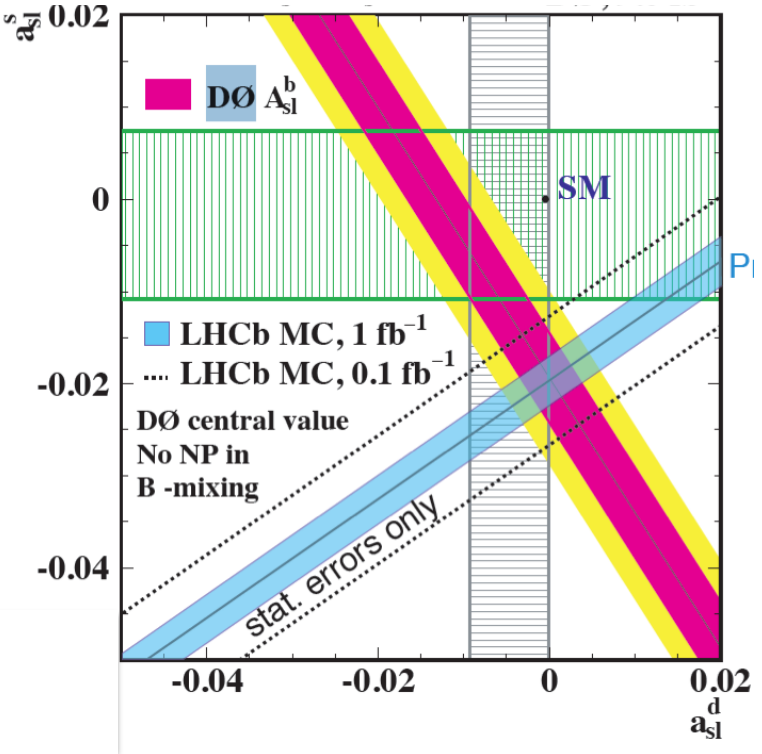
Measure *CP* violation in mixing via

$$A^b_{sl} = \frac{N_b(\mu^+\mu^+) - N_b(\mu^-\mu^-)}{N_b(\mu^+\mu^+) + N_b(\mu^-\mu^-)}$$

Asymmetry is a linear combination semileptonic charge asymmetries of B^0_d and B^0_s

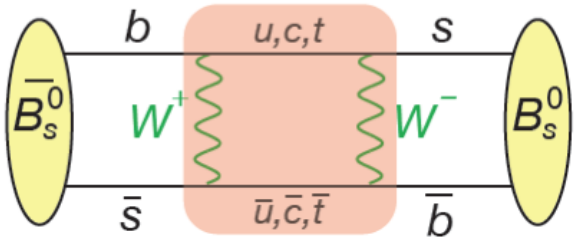
$$A^b_{sl} = C_d a^d_{sl} + C_s a^s_{sl} \;; \qquad a^b_{sl} = \frac{\Gamma(\overline{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(\overline{B} \to \mu^+ X) + \Gamma(B \to \mu^- X)}$$

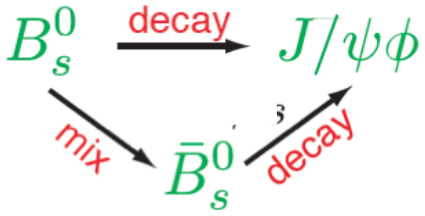
Coefficients depend on mean mixing probability and production fractions

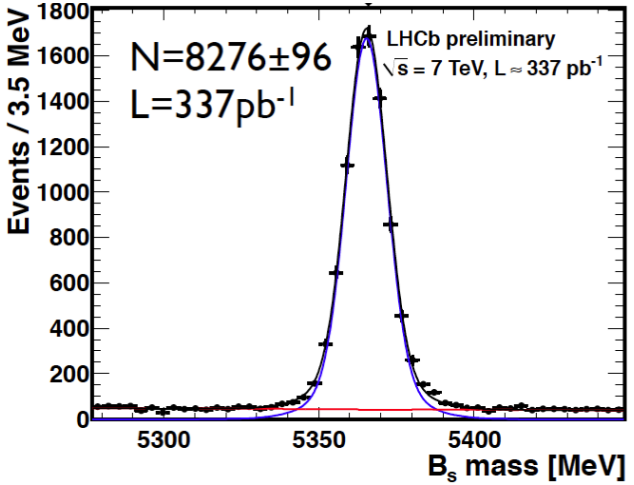


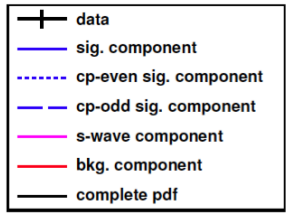
- LHCb starts with CP non-invariant initial state:
  - measure difference between Bd and Bs asymmetries
- LHCb MC sensitivity study with 1 fb^{-1}

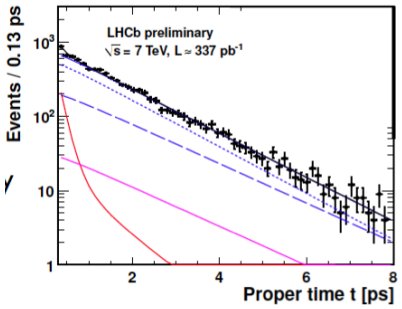
CP violation in Bs→J/Ψϕ

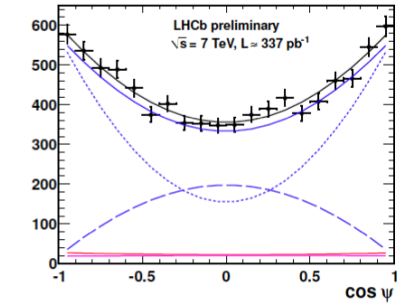


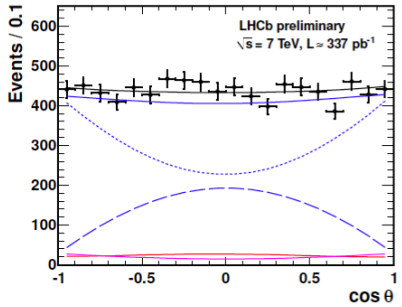


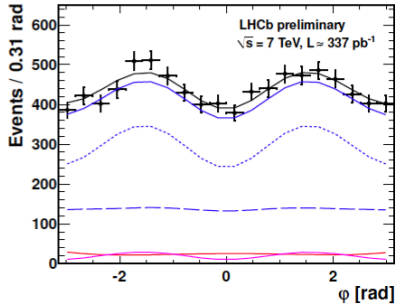


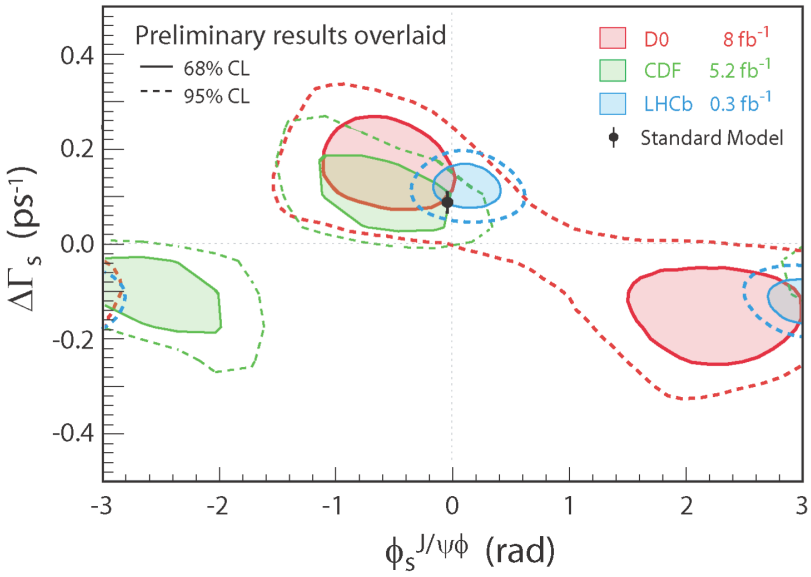












LHCb:

Most precise measurement of ϕ_s

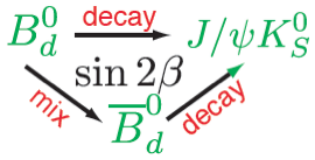
- ϕ_s = 0.13 ± 0.18 (stat) ± 0.07 (syst) rad
- Consistent with SM

4 σ Evidence for $\Delta\Gamma_s \neq 0$:

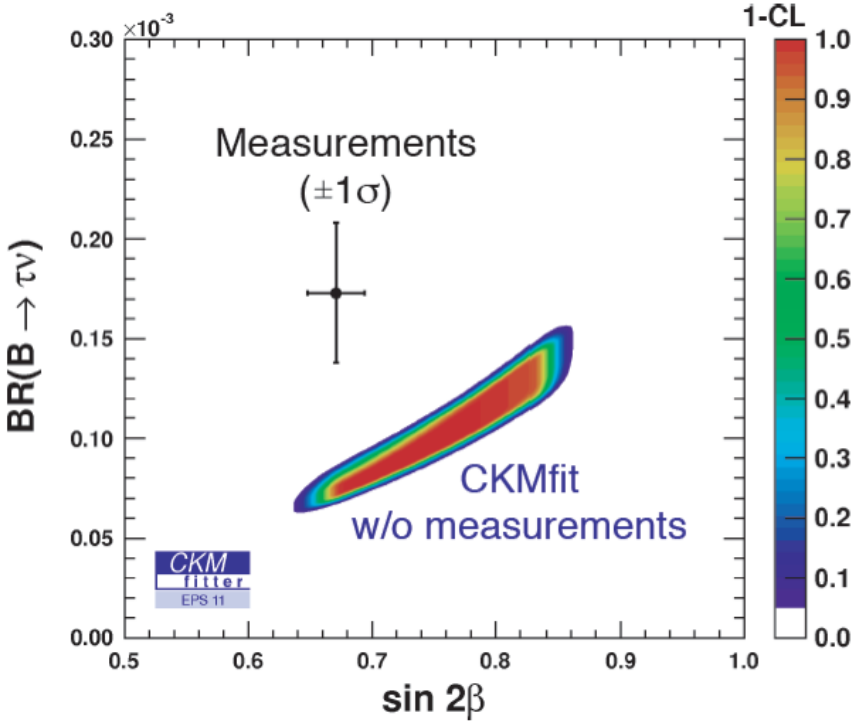
- $\Delta\Gamma_s$ = 0.123 ± 0.029 (stat) ± 0.008 (syst) ps^{-1}
- Γ_s = 0.656 ± 0.009 (stat) ± 0.008 (syst) ps^{-1}

New physics in B_d system?

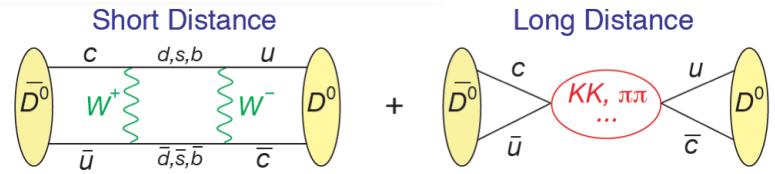
Golden mode,
***B* Factories**



- Tension between observed values of $\sin(2\beta_{cc})$ and $\mathcal{B}(B^{\pm} \to \tau^{\pm}\nu)$ and predictions from fit

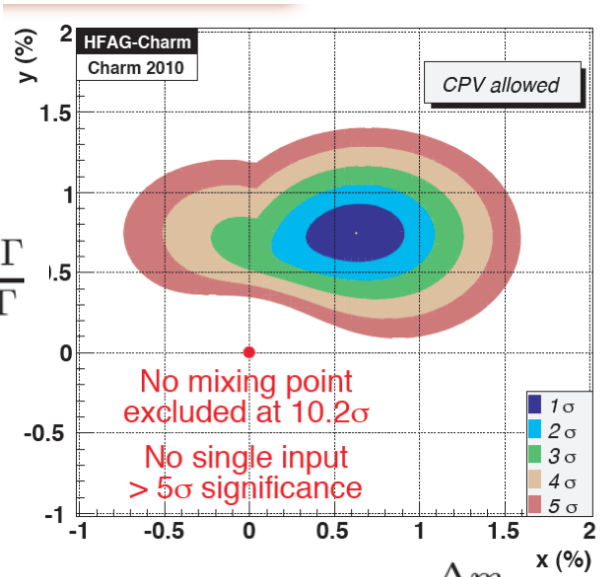


D^0 mixing



Large uncertainty in SM mixing rate
more difficult to identify New Physics contributions

$$y = \frac{\Delta\Gamma}{2\Gamma}$$

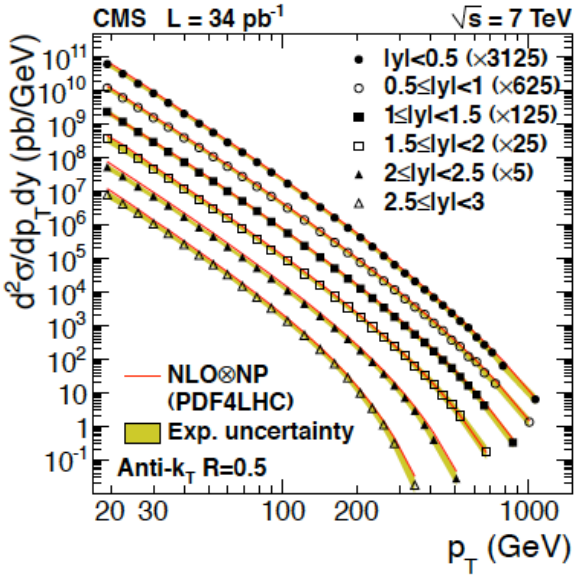


$$x = \frac{\Delta m}{\Gamma}$$

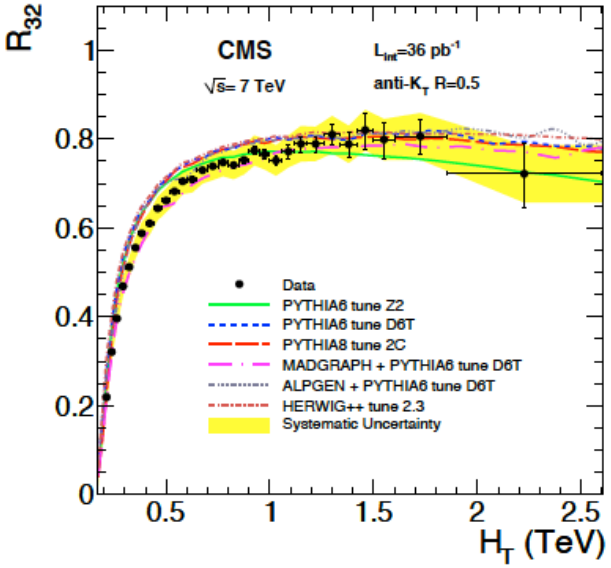
Measurements so far consistent with zero CP violation

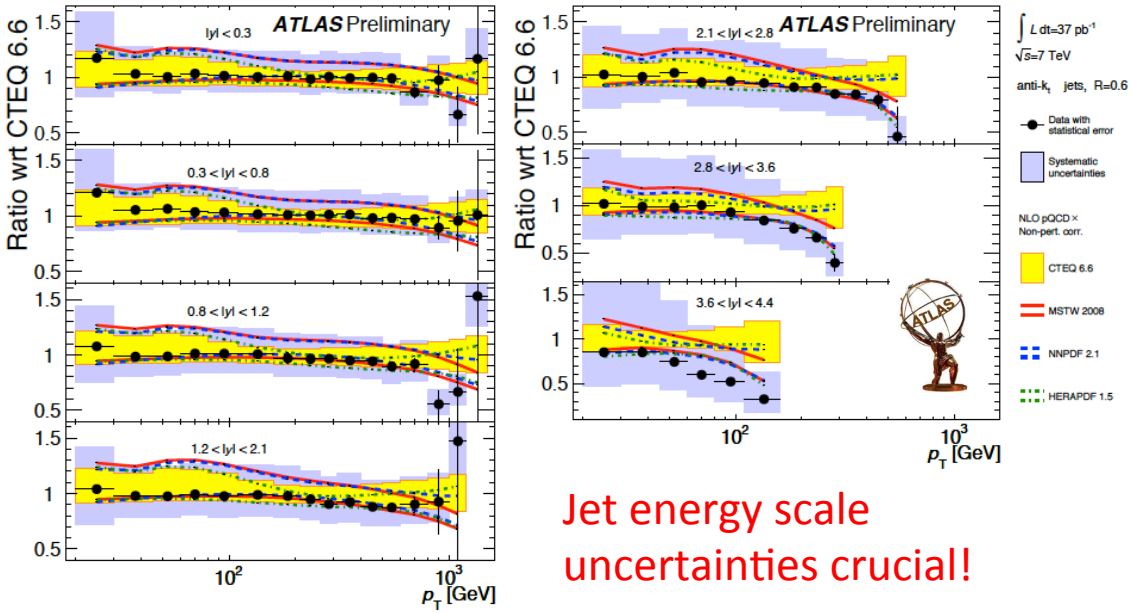
Jets and QCD

Ratio of 3- to 2-jet rates

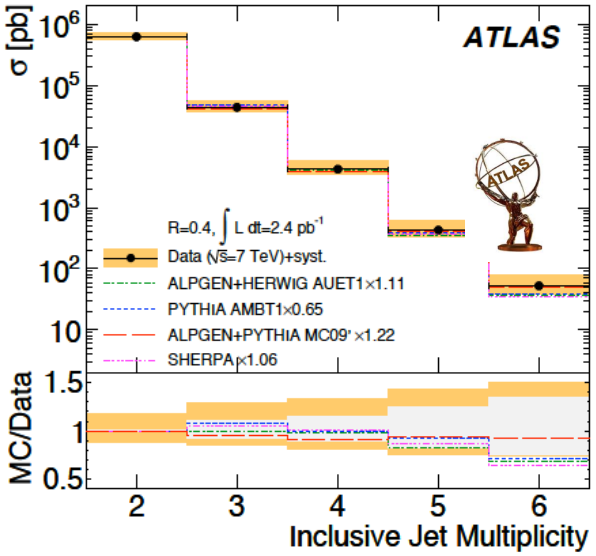


Inclusive jet p_T

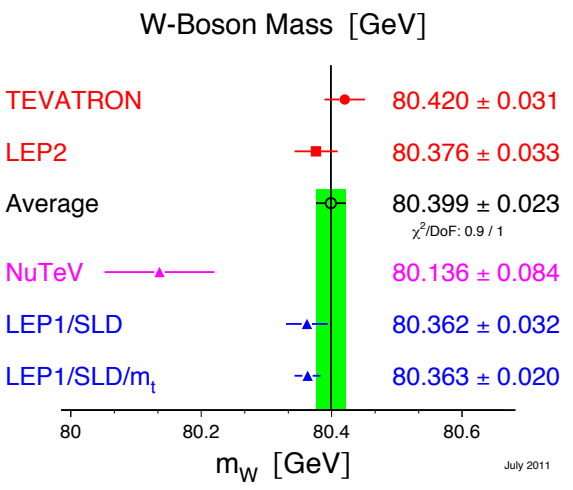


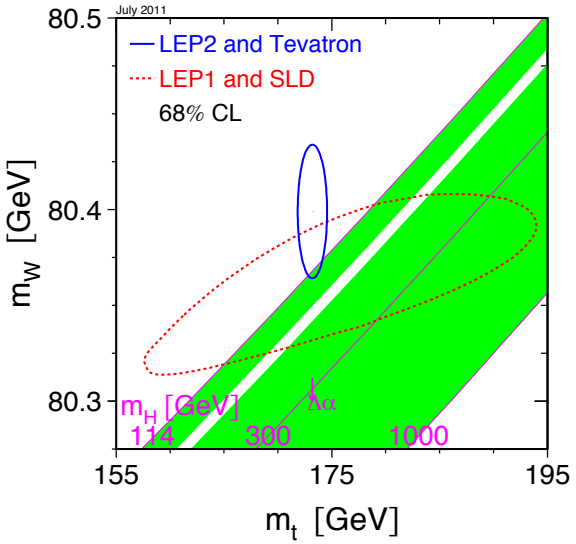


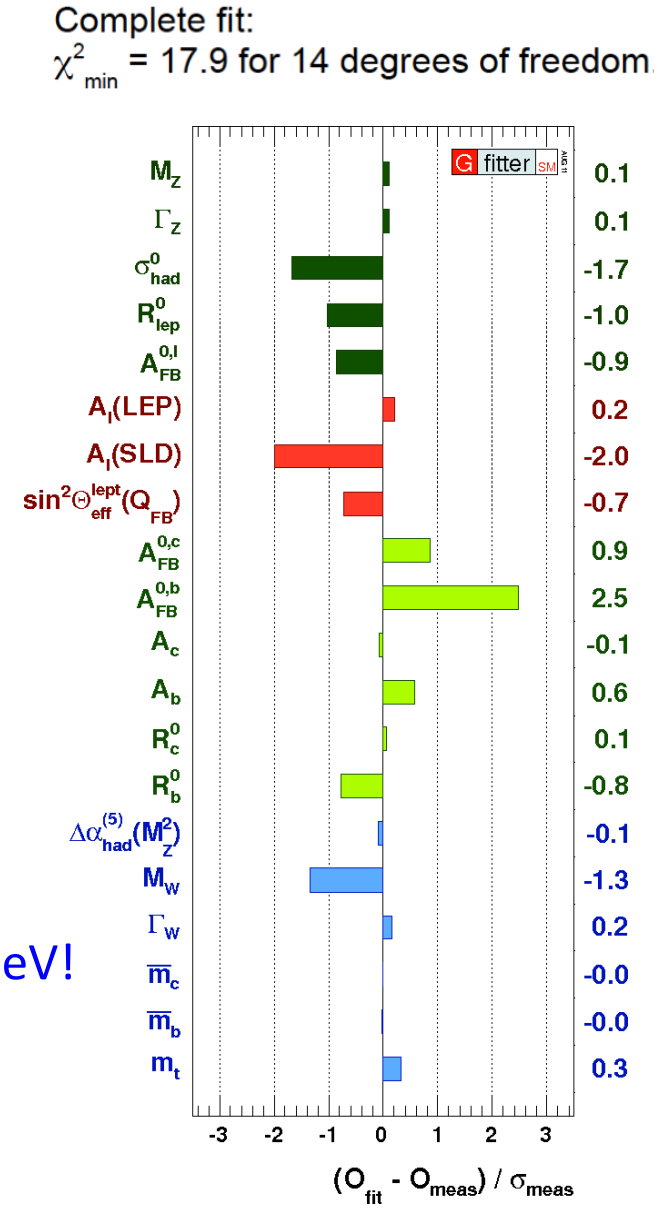
Jet energy scale uncertainties crucial!

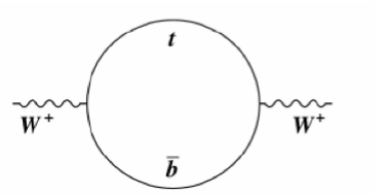


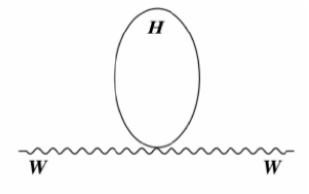
Precision EW Fit Summary







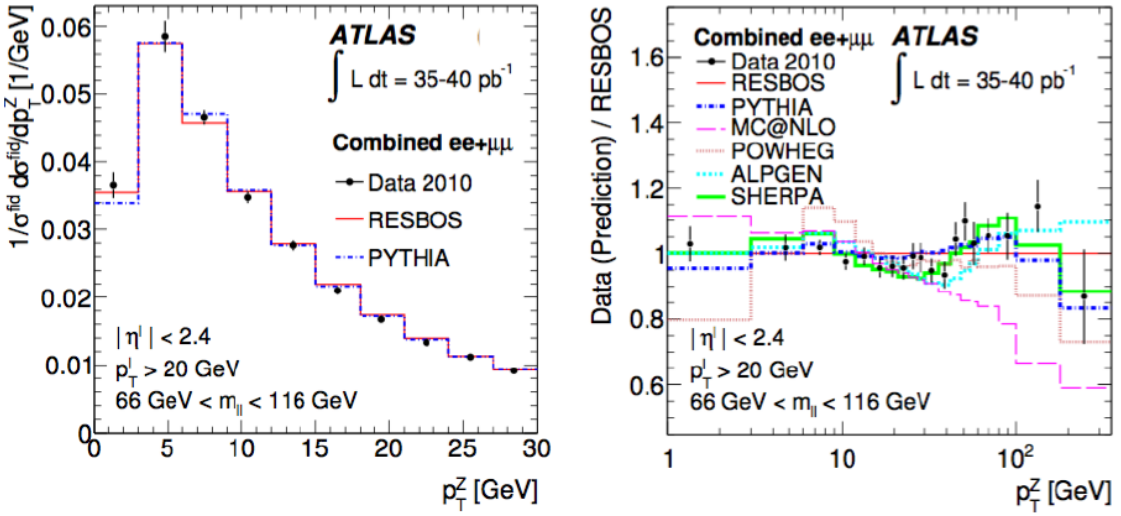




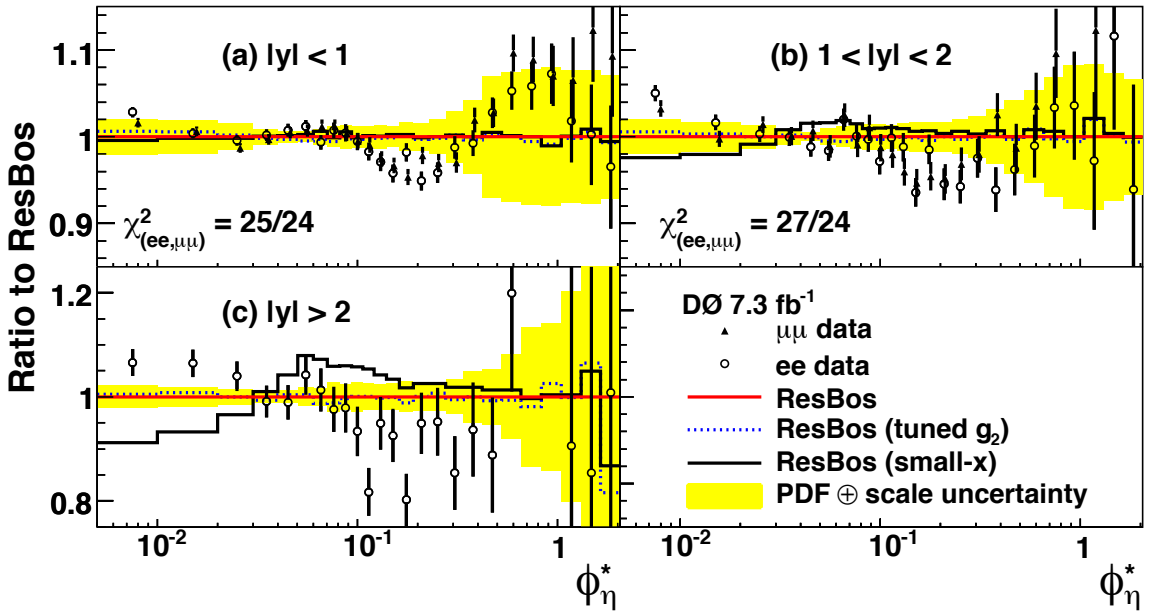
- Δm_t (Tevatron) = 0.9 GeV
- Equal contribution to Δm_H would require Δm_W = 5 MeV!
- Possibly expect Δm_W = ~15 MeV per experiment?
  - Will require many `engineering' measurements
    - PDFs, vector boson p_T, etc.

Vector boson p_T

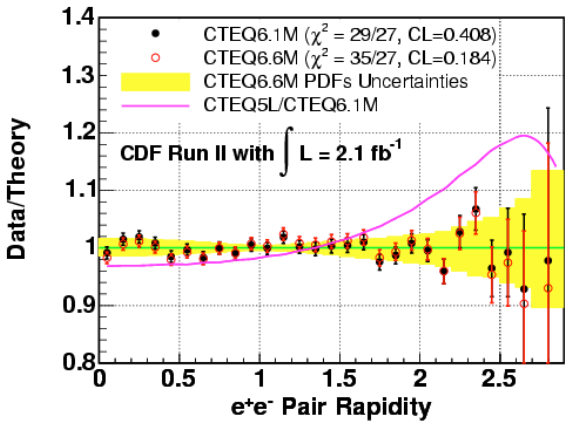
- First measurements from the LHC



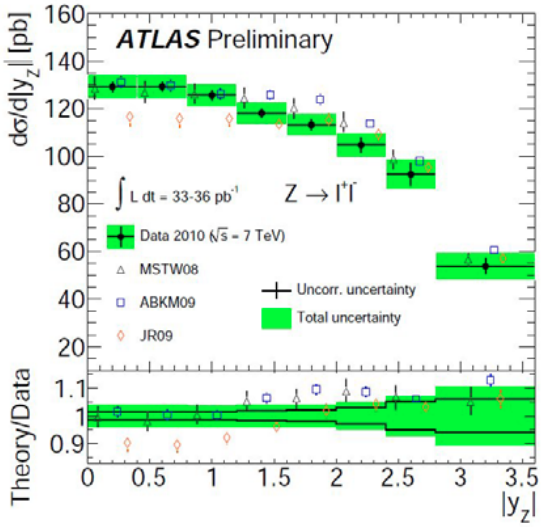
- A new idea from DØ: ϕ^*_η
  - Very much reduced systematic uncertainties
  - Statistics limited even with ~1M Z



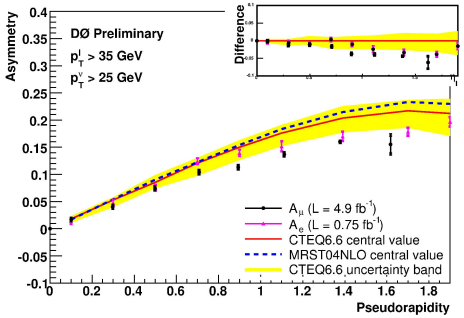
Parton Distribution Functions and vector boson rapidities

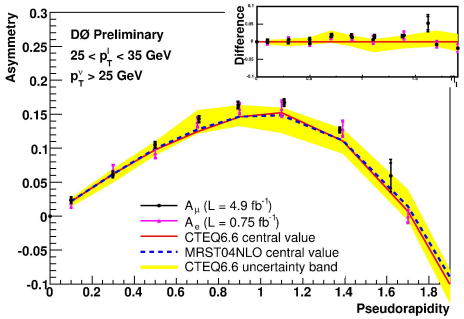


Z boson rapidity at the Tevatron and the LHC

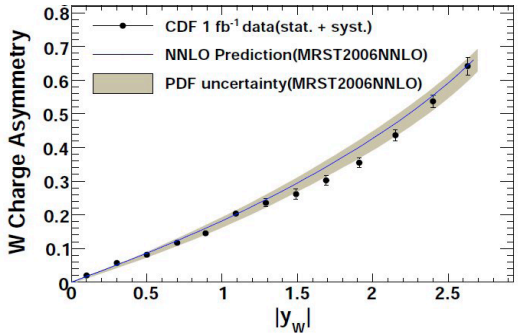


Charged lepton A_{FB} in lepton p_T bins (DØ)



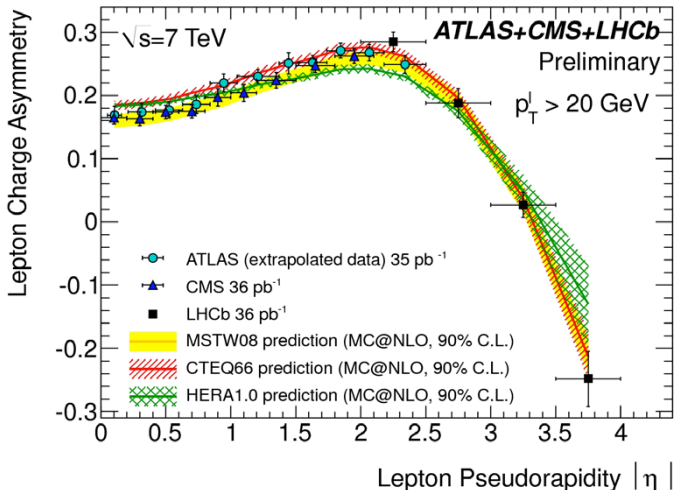


Inclusive W boson A_{FB} (CDF)

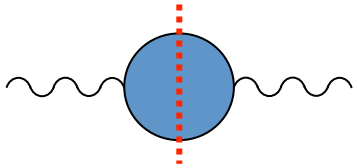


- N.B. Models unable to describe well lepton p_T dependence
- Care needed when extracting W rapidity (and thus PDF information)

GPDs + LHCb cover huge range in lepton pseudorapidity (and thus x, Q^2)

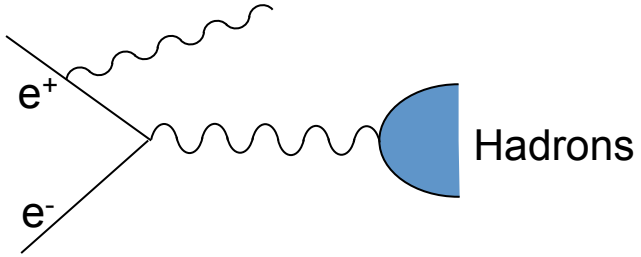


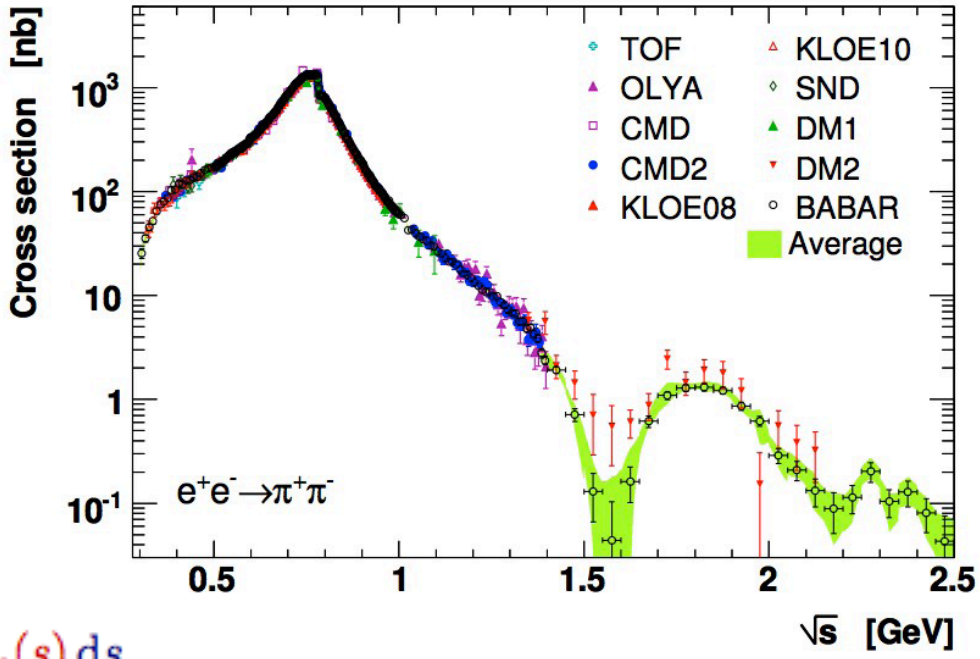
Running of α



$$\alpha(q^2) = \alpha \,/\, \left(1 - \Delta\alpha_{\rm lep}(q^2) - \Delta\alpha_{\rm had}(q^2)\right)$$

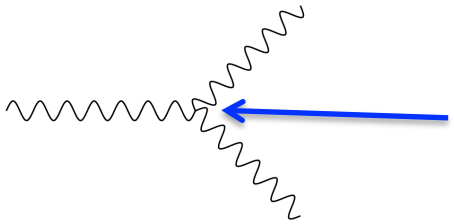
- Uncertainty dominated by $\Delta\alpha_{\rm had}(q^2)$
  - effect of qq loops at low q^2
- Cannot be calculated from first principles in pQCD
- Experimentally accessible by:
  - direct scans
  - radiative return





$$\Delta\alpha^{(5)}_{\rm had}(q^2) = -\frac{q^2}{4\pi^2\alpha} P \int_{m_\pi^2}^{\infty} \frac{\sigma^0_{\rm had}(s)\,{\rm d}s}{s - q^2}$$

Electroweak di-boson production (leptonic modes)

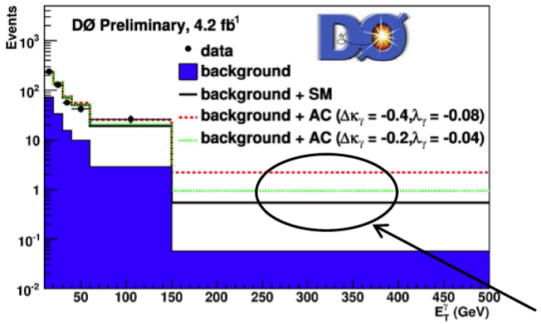


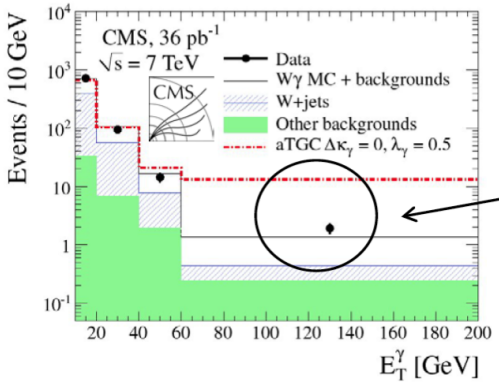
Sensitive to potential new physics contributions, e.g., at triple gauge coupling vertices

Current observations (small statistics) consistent with SM predictions

- Long term area of study at LHC!

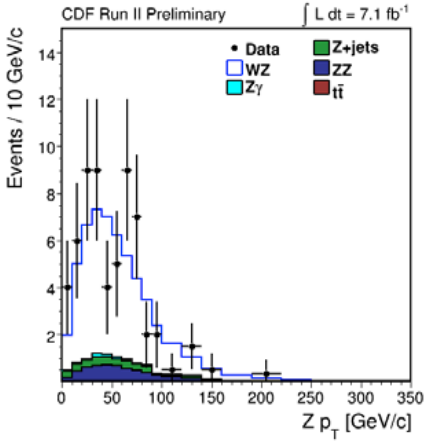
Wγ

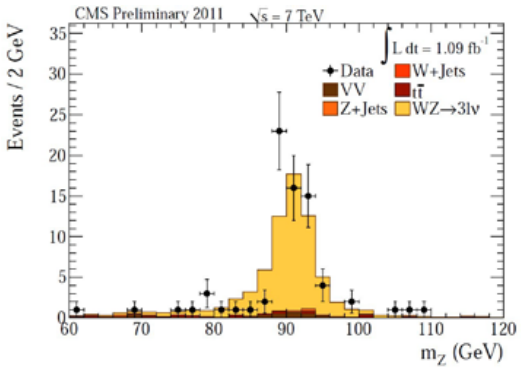




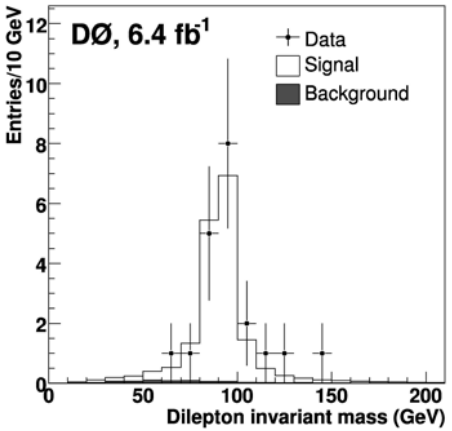
Expect signal here

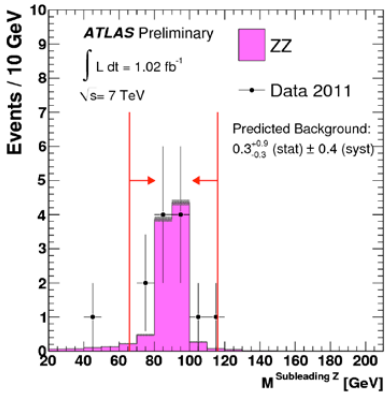
WZ





ZZ

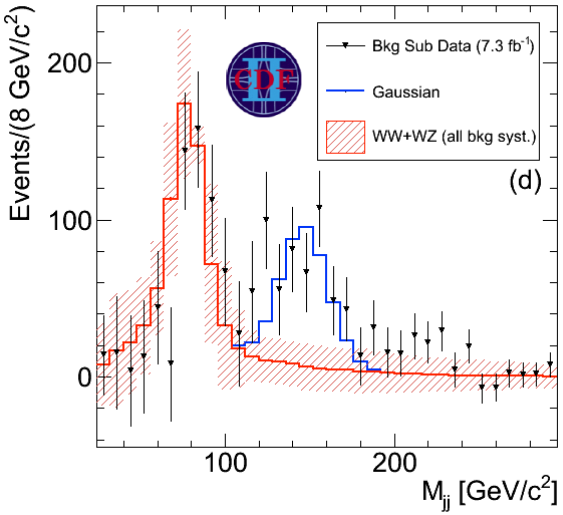


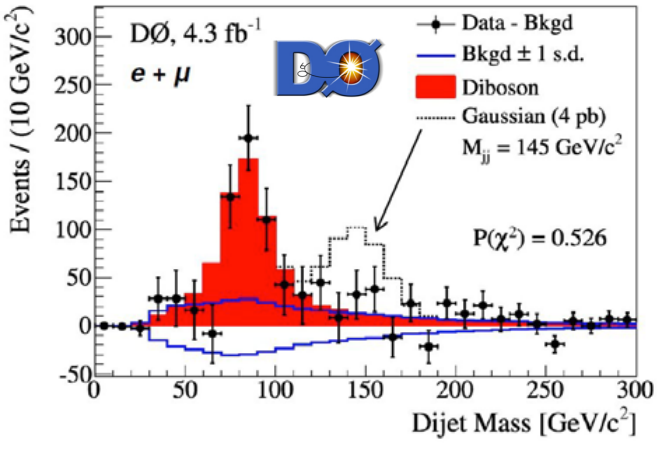


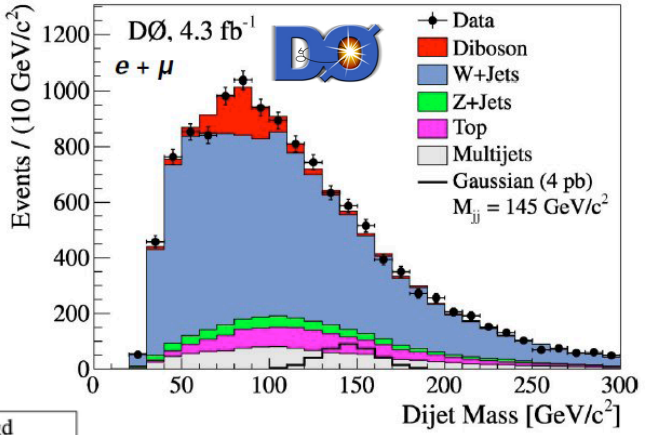
WZ+ZZ production (lepton+jet modes)

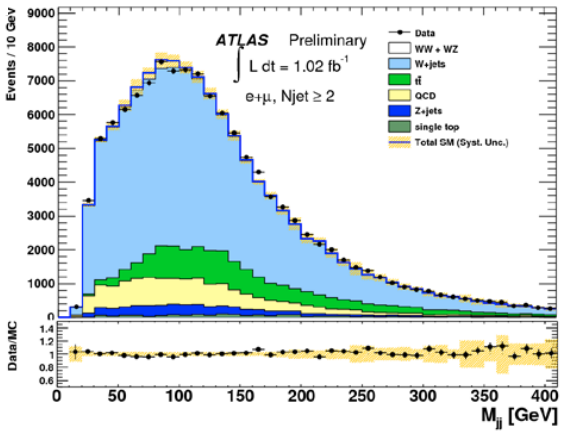
- More challenging because of large V+jet backgrounds, but clear signals for WZ+ZZ observed at the Tevatron

CDF excess ..... ruled out by DØ





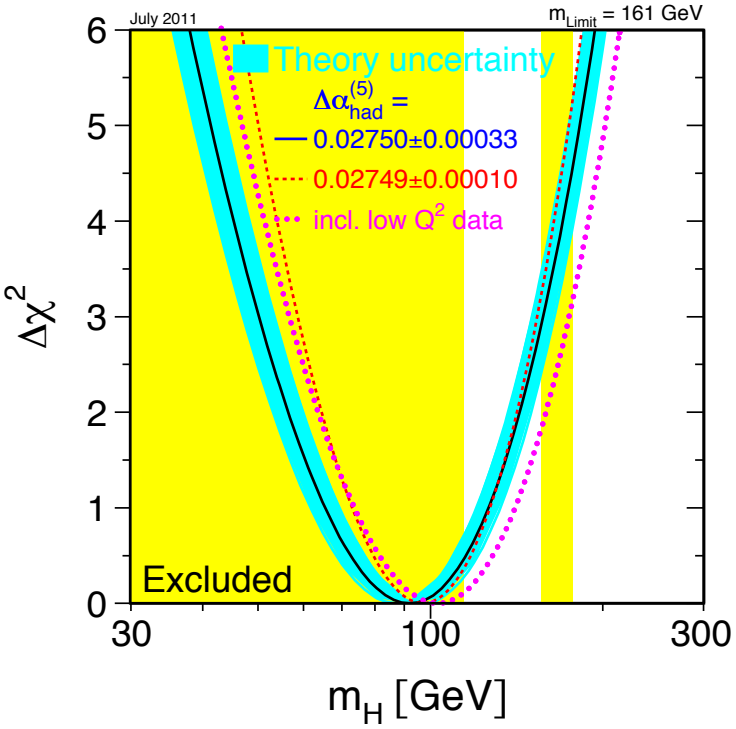


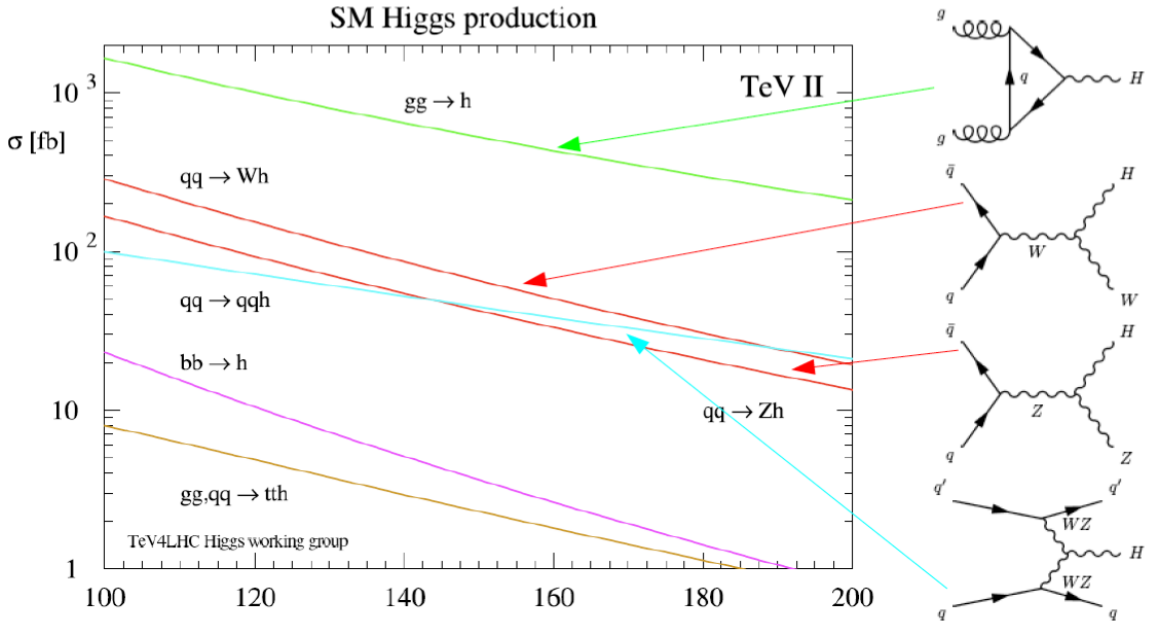


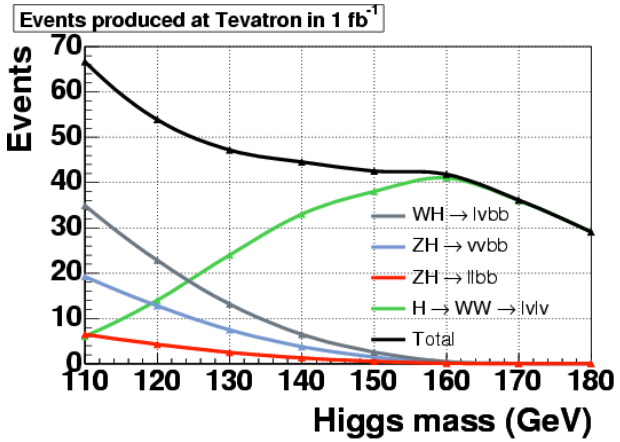
..... even more challenging at the LHC!

Higgs searches

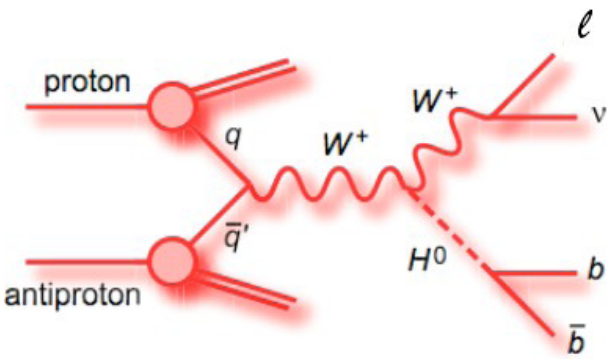
- EW fit
  - $m_H < 161$ GeV @ 95% CL
- Region preferred by EW data is within reach of Tevatron and LHC experiments



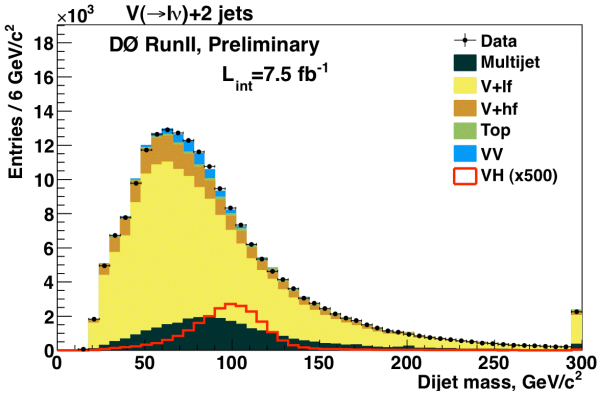


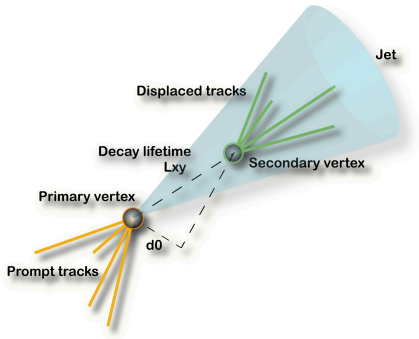


Higgs searches

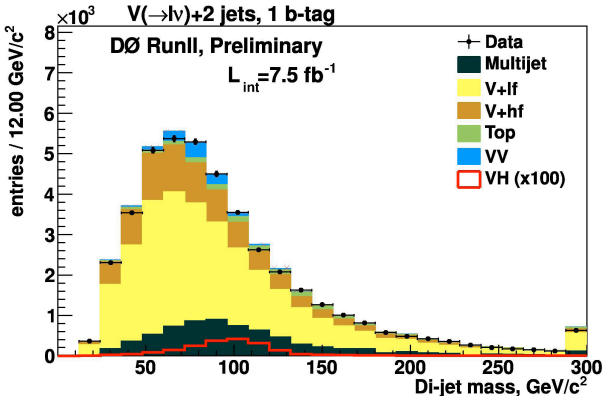


no b-tagging

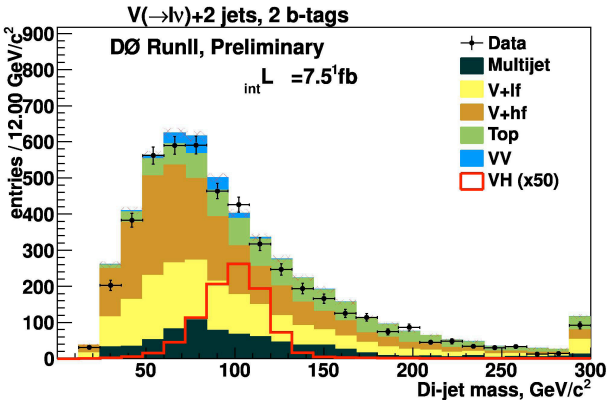




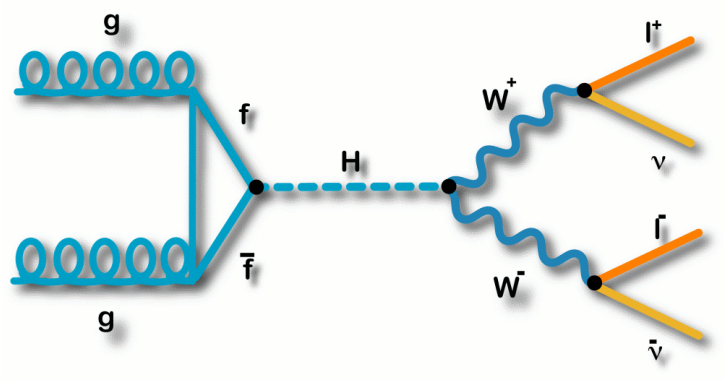
1 b-tag



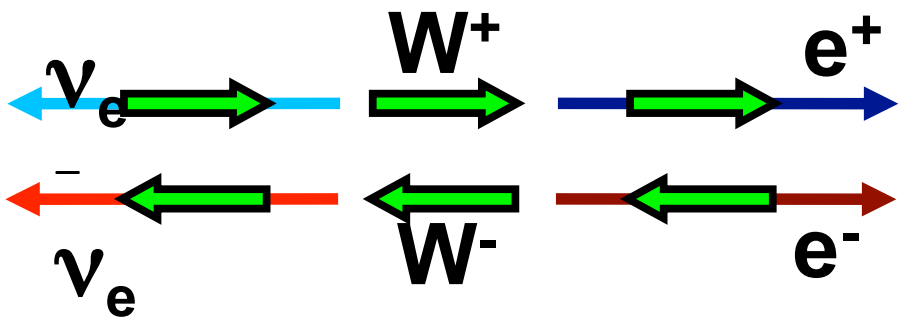
2 b-tags



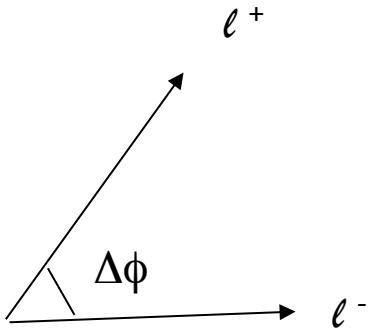
Higgs Searches at High Mass

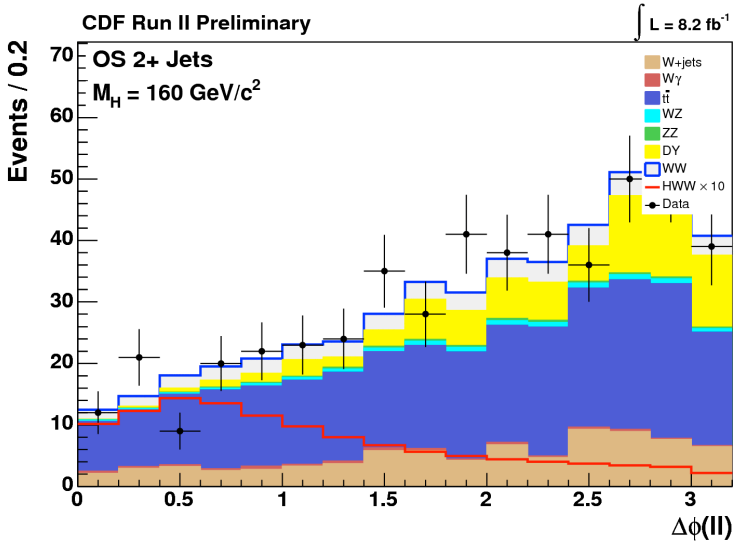


Higgs is a spin zero particle



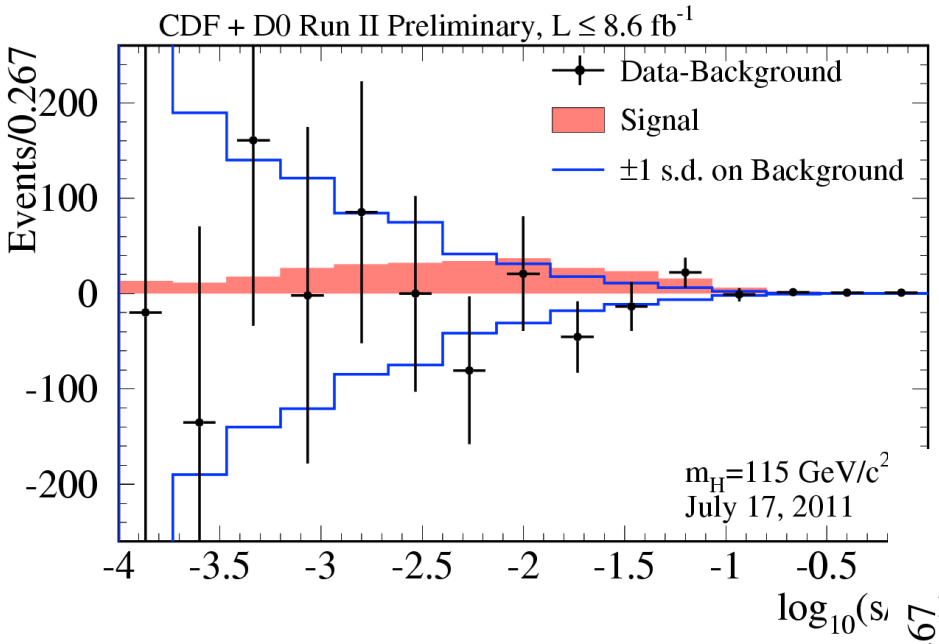
- Look for leptonic decays of WW
- Look at azimuthal angle between the two charged leptons
  - Higgs: small $\Delta\phi$
  - Standard WW events: large $\Delta\phi$

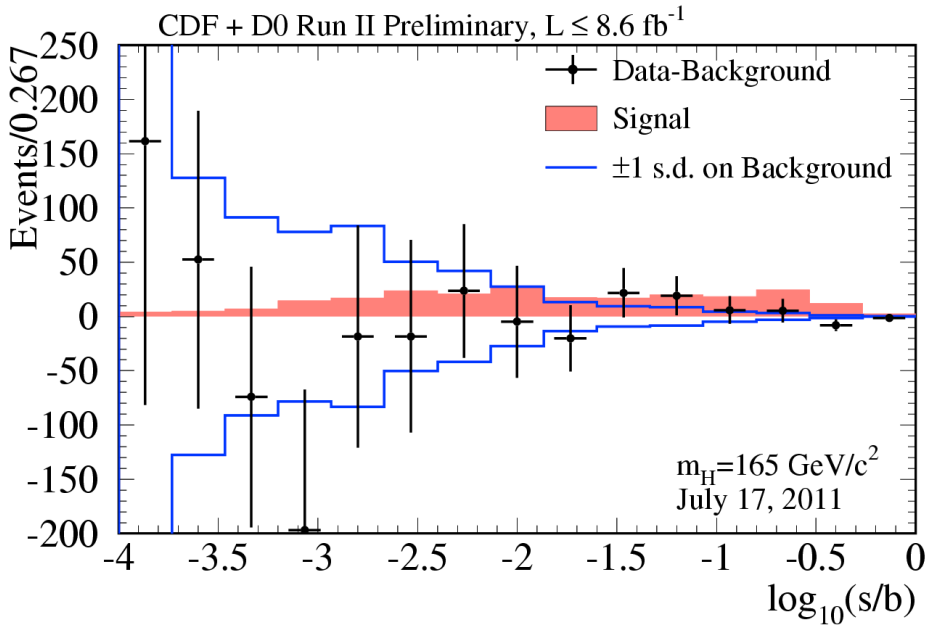




Higgs x 10

Higgs searches: background subtracted distributions



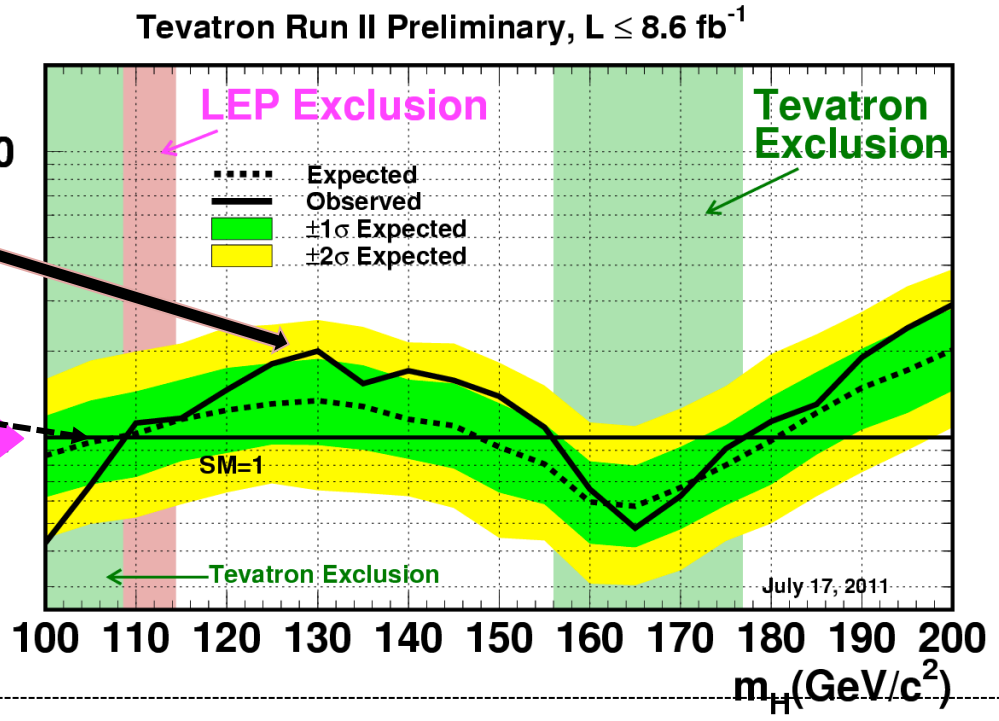


Current CDF+DØ Combined Limits

- In the absence of a signal
  - Set a limit on the allowed cross section times branching ratio for Higgs production
    - that is, how large could cross section times branching ratio for Higgs production be before it would have been visible?
  - Express limit as a ratio to the cross section expected in the Standard Model

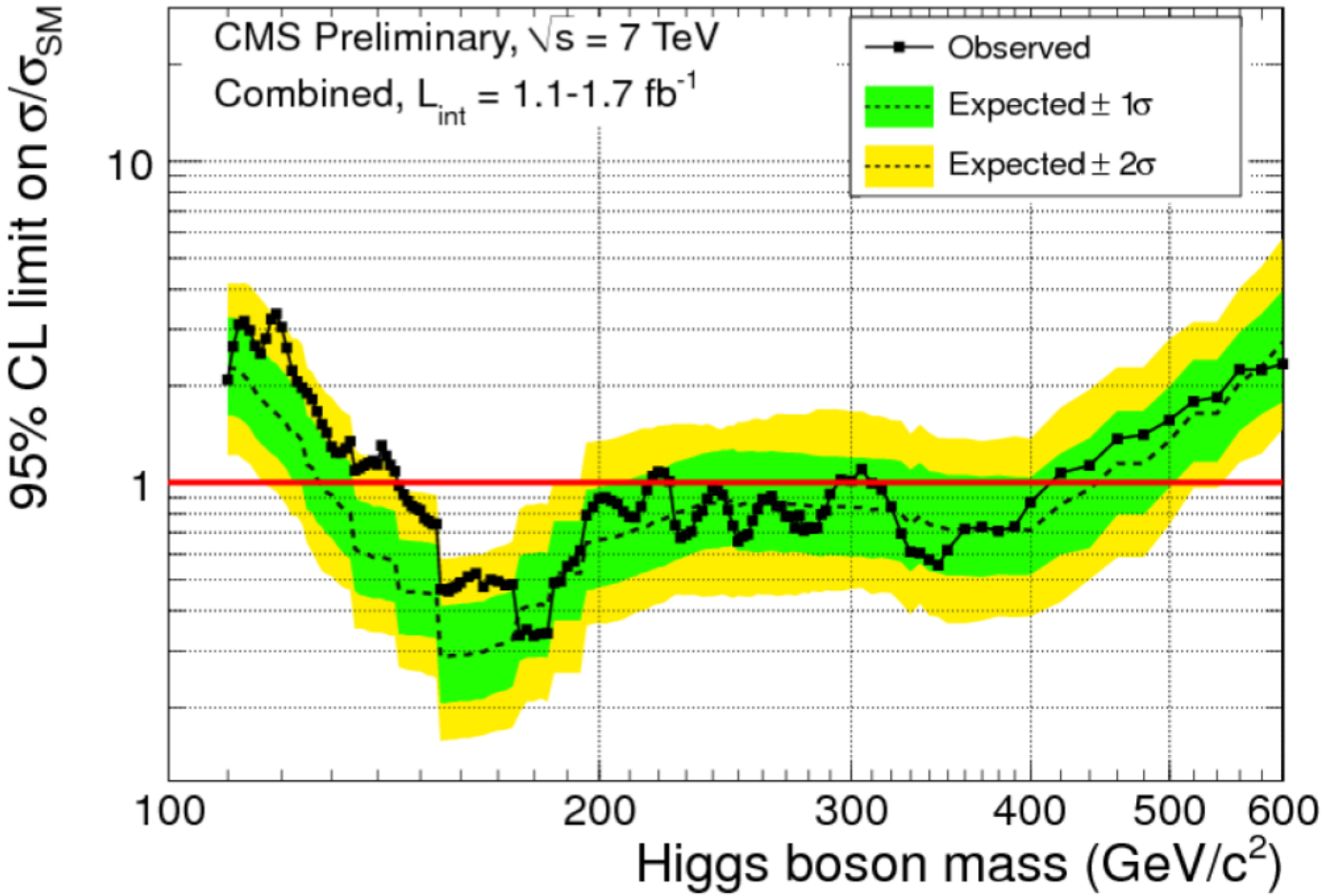
"Observed limit" obtained from CDF+DØ data

"Expected limit" obtained by repeating the analysis on a large number of "background-only" Monte Carlo "experiments"



Standard Model Higgs ruled out @ 95% CL if the limit reaches this level!

Higgs searches @ CMS

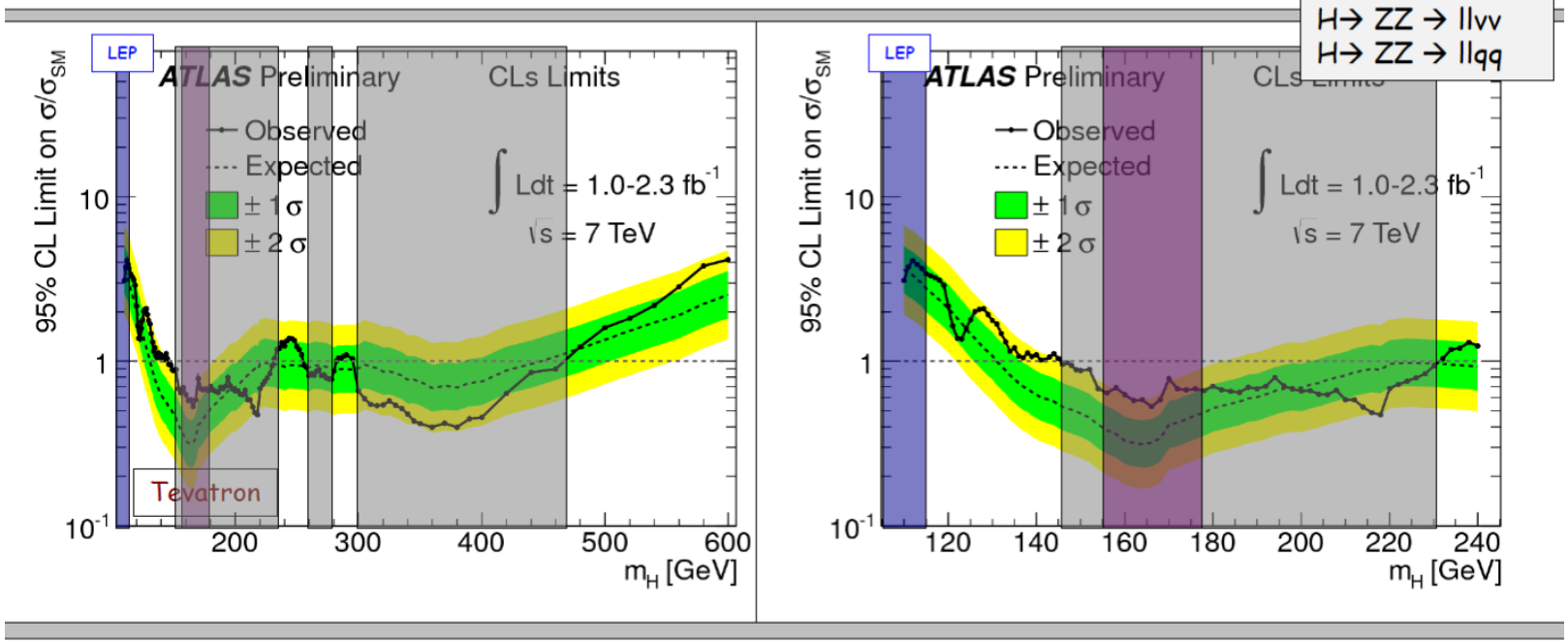


Expected exclusion mass range: 130 – 440 GeV
Observed exclusion mass range: 145-216, 226-288, 310-400 GeV

Higgs searches @ ATLAS

All channels together → combined constraints

H→γγ
H→ ττ
W/ZH→ lbb+X
H→ WW(*)→ lνlν
H→ ZZ(*) → 4l
H→ ZZ → llνν
H→ ZZ → llqq

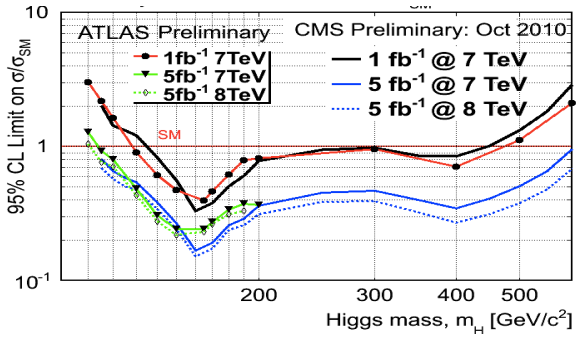


Excluded by ATLAS at 95% CL : 146-466 GeV, except 232-256, 282-296 GeV
Expected if no signal at 95% CL : 131-447 GeV

- LHC provides first direct exclusion (95% CL) of a large mass range until now unexplored
- The best-motivated low-mass region (EW fit: m_H < 161 GeV 95% CL) still open to exploration
- Data are within ±2σ of expectation for no signal over full m_H range → no significant excess

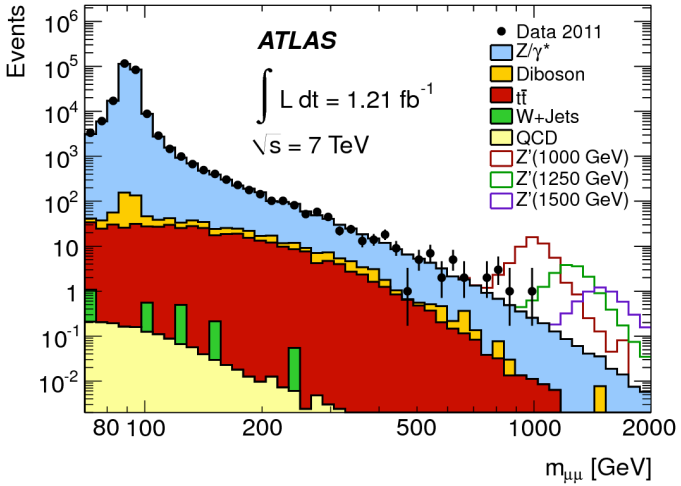
SM Higgs prospects

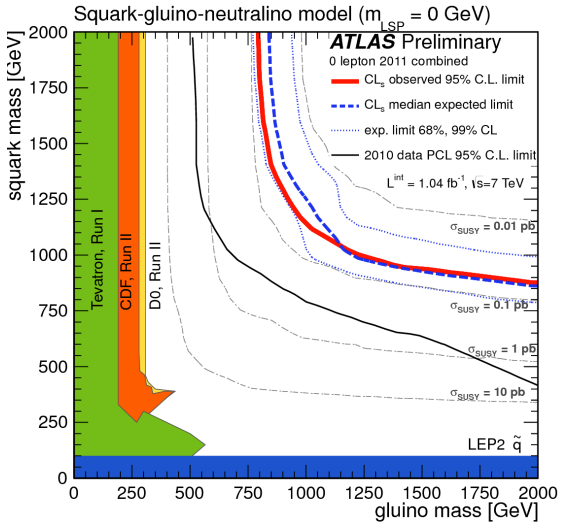
- The gold standard for SM Higgs discovery or exclusion is the same: 5σ (one-sided CL ~3×10^{-7})
  - Finding the SM Higgs is clearly an important discovery, but ….
  - Excluding the SM should be regarded (and presented to the outside world) as a discovery of equal or greater significance
- The most challenging region is for M_H around 114 GeV:
  - Tevatron and LHC searches are complementary
    - Tevatron (WH & ZH, with H➔bb), LHC (H➔γγ)
- With roughly 10 fb^{-1} per experiment at both Tevatron and LHC expect to reach combined 5σ sensitivity over the entire range $114 < M_H < 600$ GeV
- Either outcome (exclusion or discovery) will be just the start of a major programme of work requiring:
  - Years of LHC running at design luminosity and energy
  - The full capability of the LHC detectors and ingenuity of the analysers
- If light Higgs is excluded at 5σ need to discover mechanism that prevents cross section for $V_L V_L$ scattering from violating unitarity
- If light Higgs is discovered at 5σ need to measure its mass and verify that all of its properties are consistent with those expected in the SM

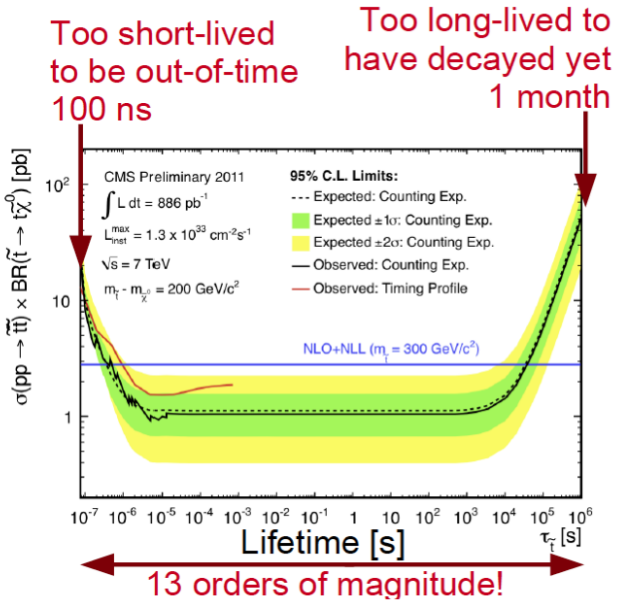


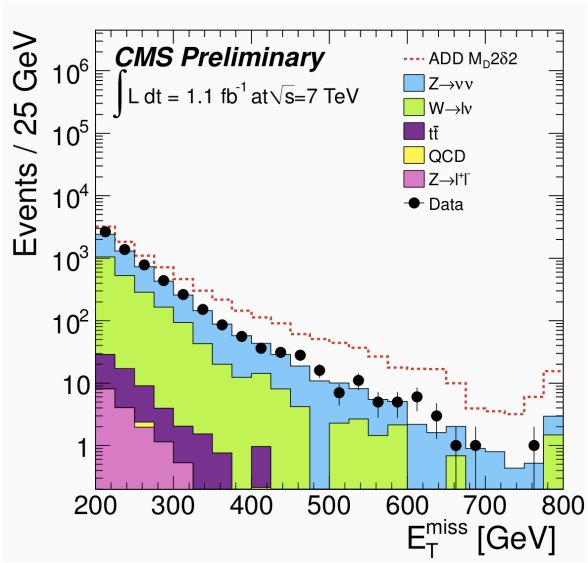
Searches for new physics

- Nothing seen yet (that the experiments are talking about ;-)



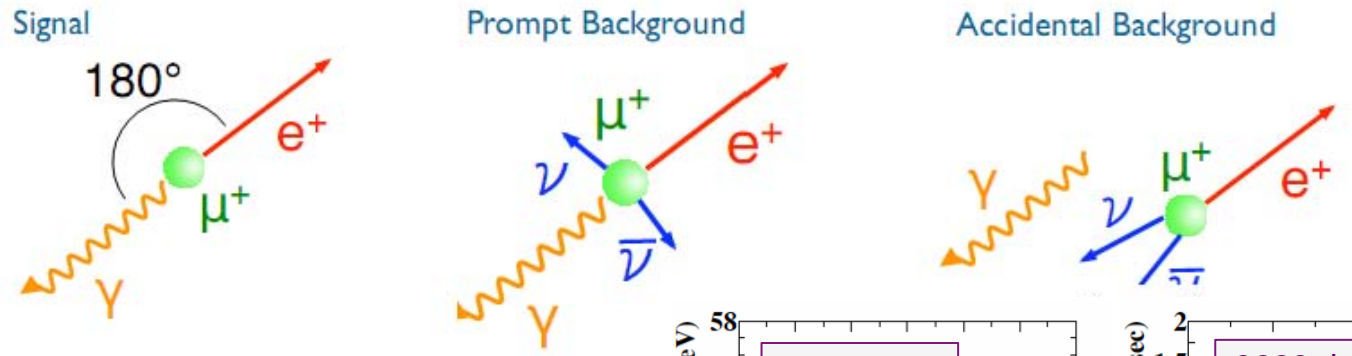




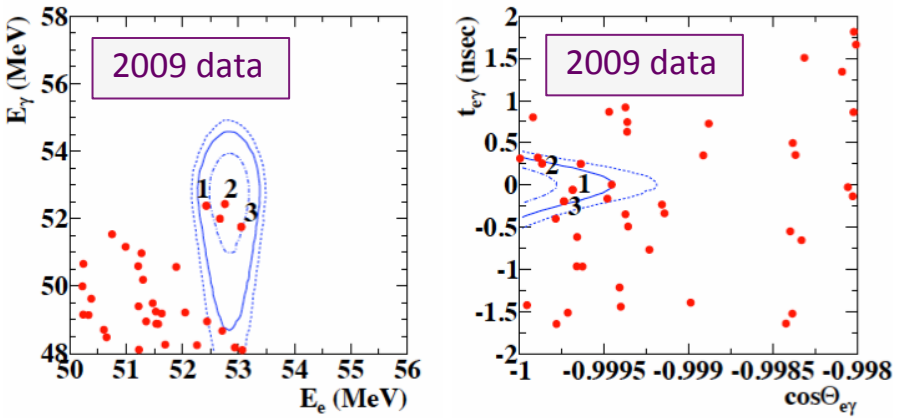


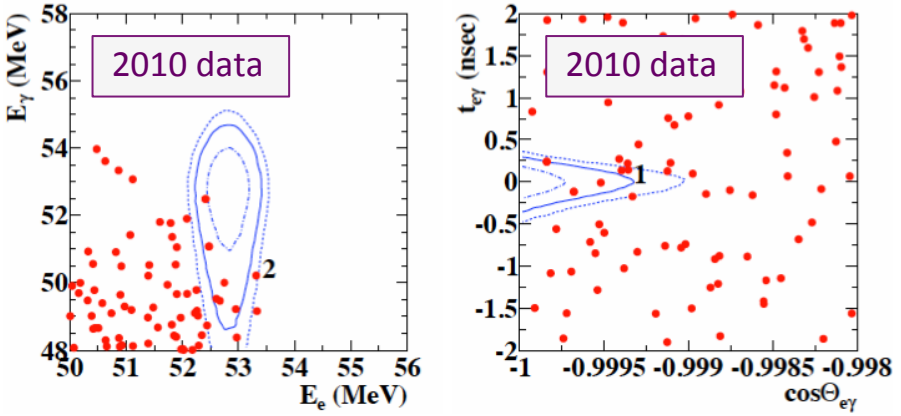
- N.B. The LHC was designed to deliver 100s fb-1 @ 14 TeV so it is early days yet!

μ➔eγ search: MEG experiment @ PSI



- Combined sample
  - 1.8 x 10^{14} μ decays
- Br(μ➔ev) < 2.4 x 10^{-12}
  - @ 90% CL

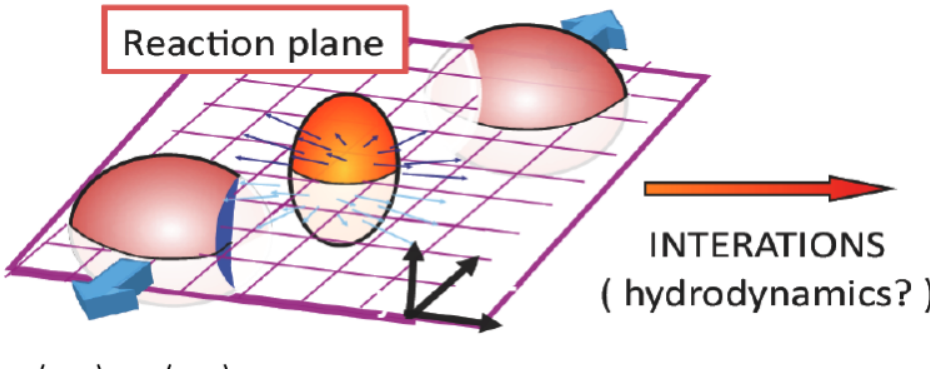


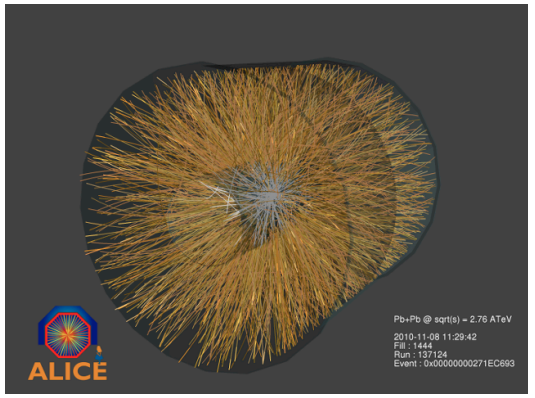


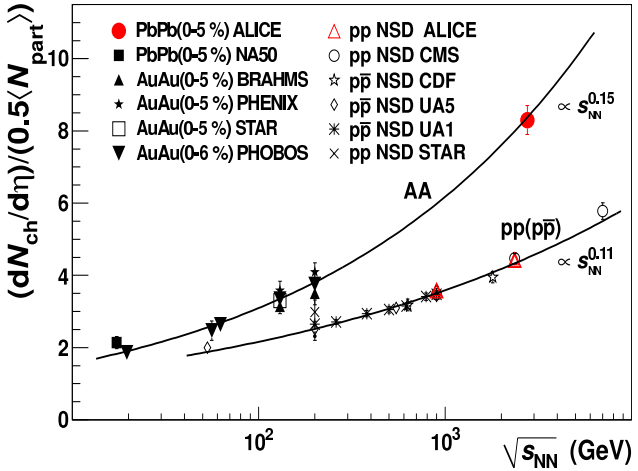
Heavy Ions

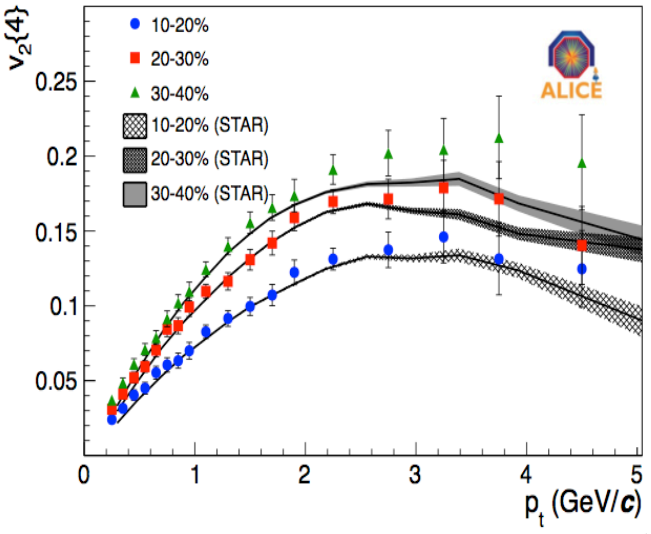
- LHC performed extremely well for the Pb-Pb run (Nov 2010)
  - delivered ~ 8 μb^{-1} in 4 weeks
    - $L > 2 \times 10^{25}\ cm^{-2}s^{-1}$, ~ 1/20 L_{max}
  - Special pp run at $\sqrt{s}$ = 2.76 TeV
    - Important for normalization of PbPb results to pp

- Azimuthal flow
  - The system produced at the LHC behaves as a very low viscosity fluid (a perfect fluid)



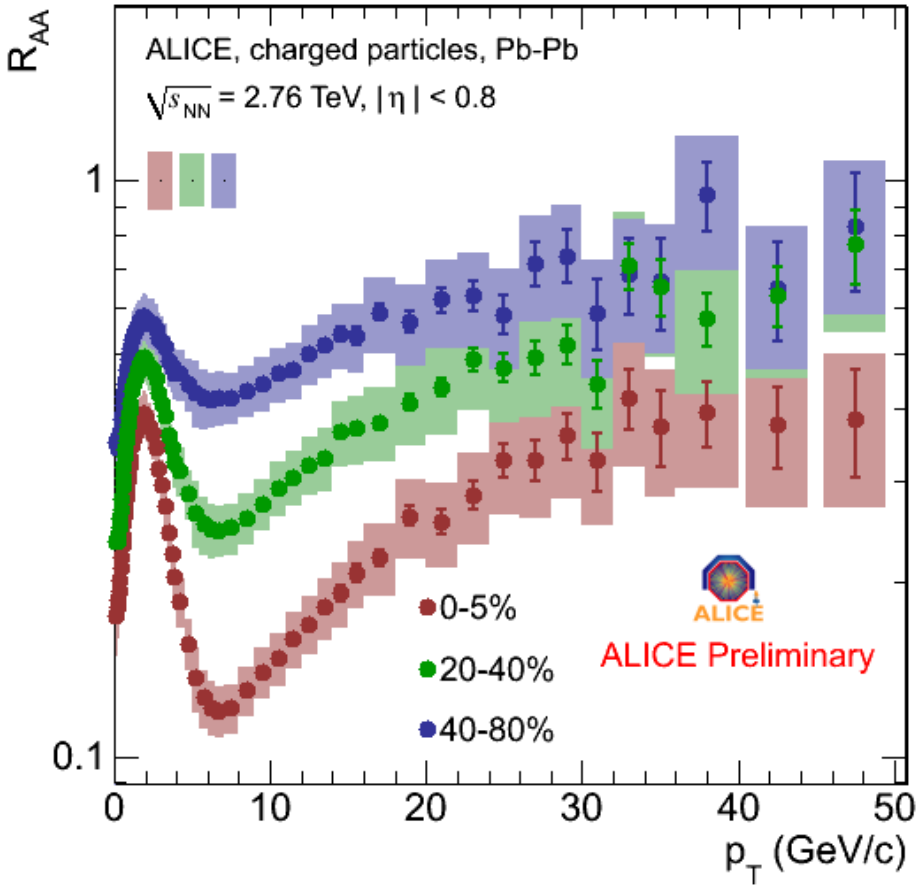






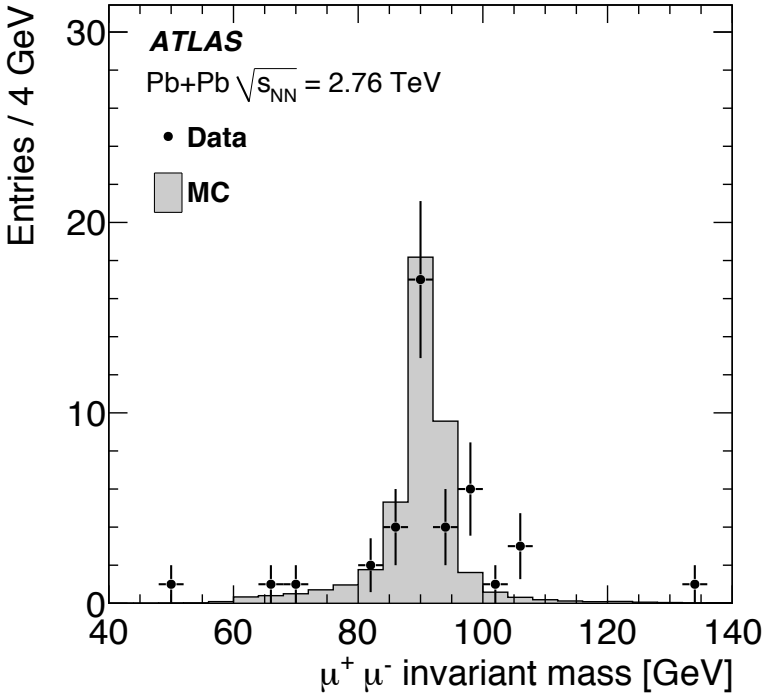
Heavy Ions

Charged particle spectra
R_{AA}: Ratio of Pb-Pb to pp



- The most central events show the greatest suppression
- Pronounced p_T dependence

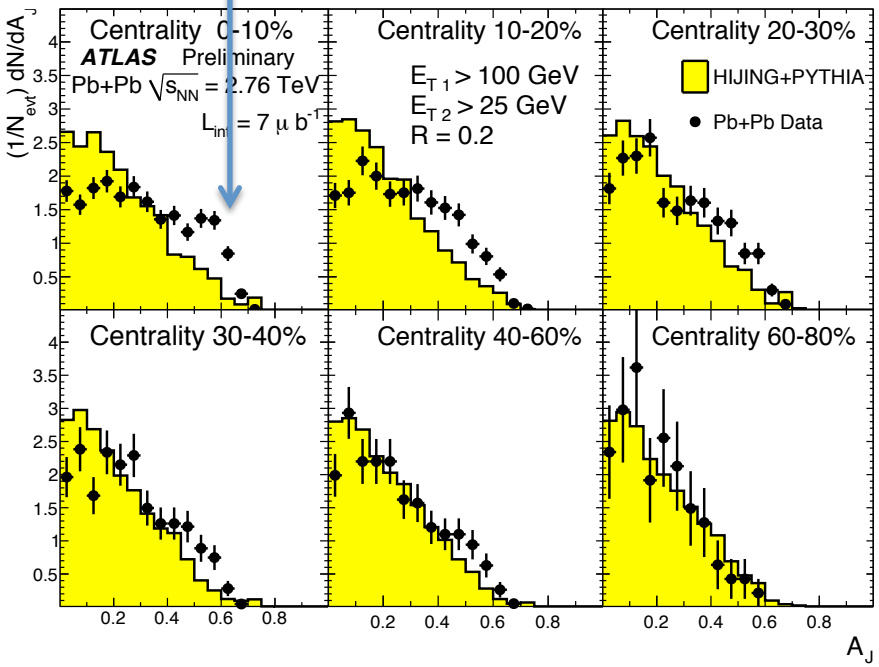
Electroweak probes

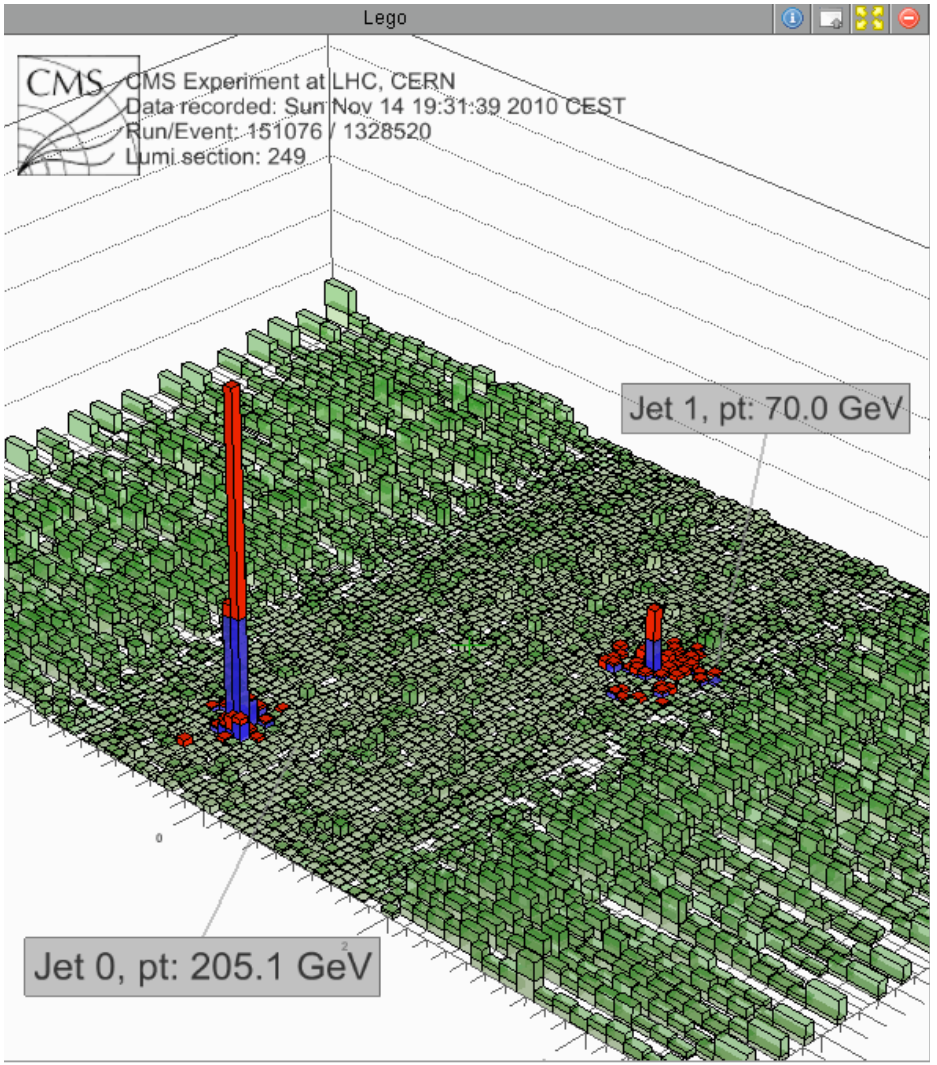


- Rate in agreement with NLO calculations, scaled by number of collisions

Heavy Ions

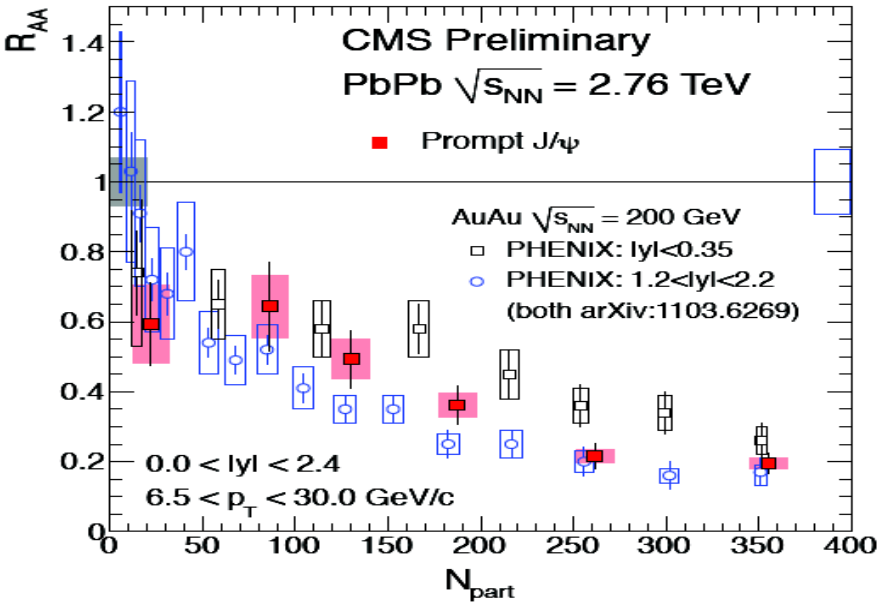
- Large dijet imbalance observed in central events
  - direct observation of parton energy loss in nuclear matter

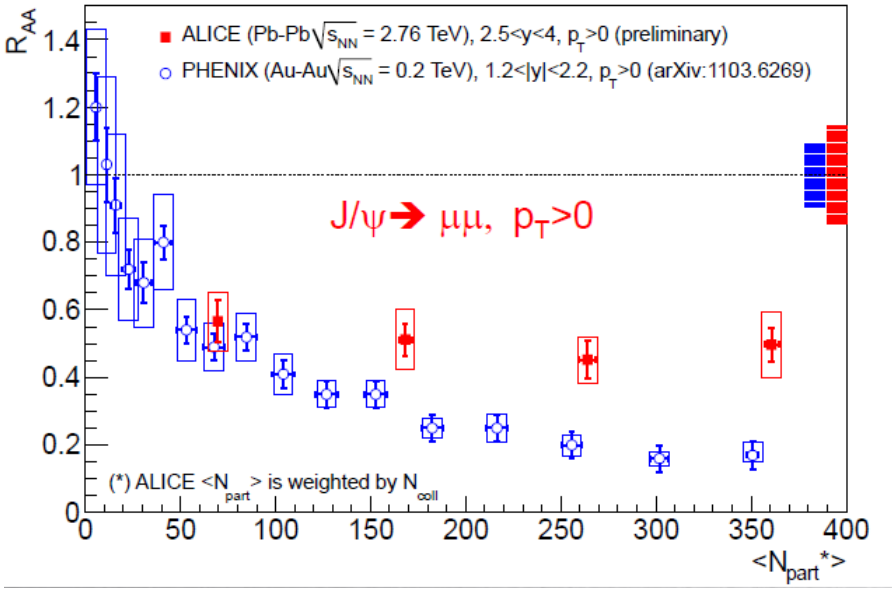




$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Heavy Ions



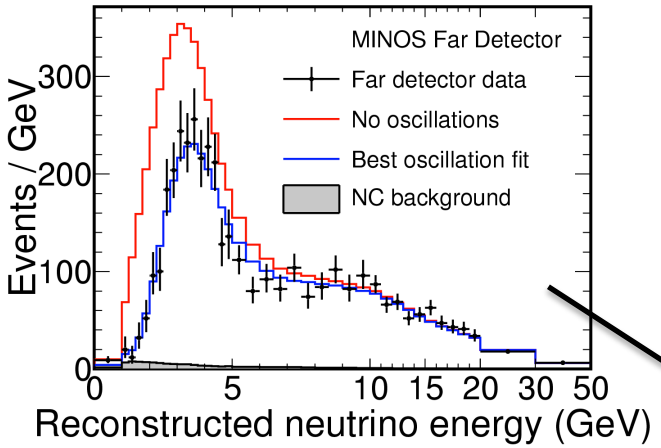


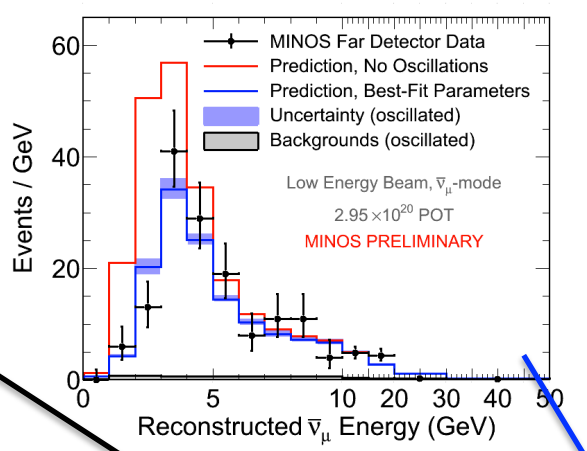
J/Ψ suppression

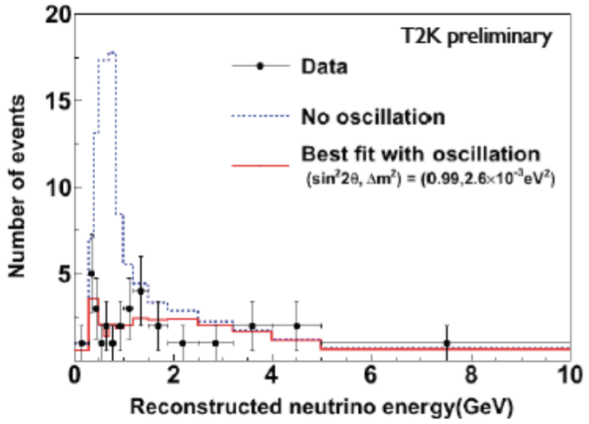
- For central rapidities similar suppression at LHC and RHIC
- Forward rapidities less suppression at LHC than at RHIC
  - N.B. |y| ranges different

ν_μ disappearance (Θ_{23})

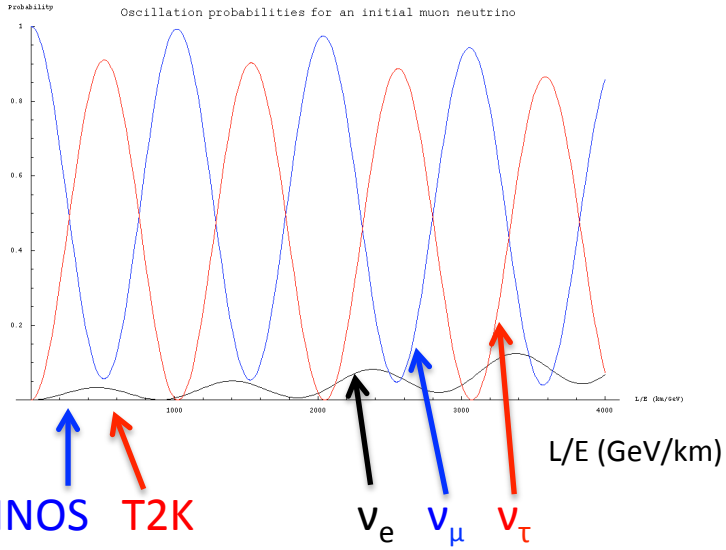
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267\Delta m^2 L/E)$$

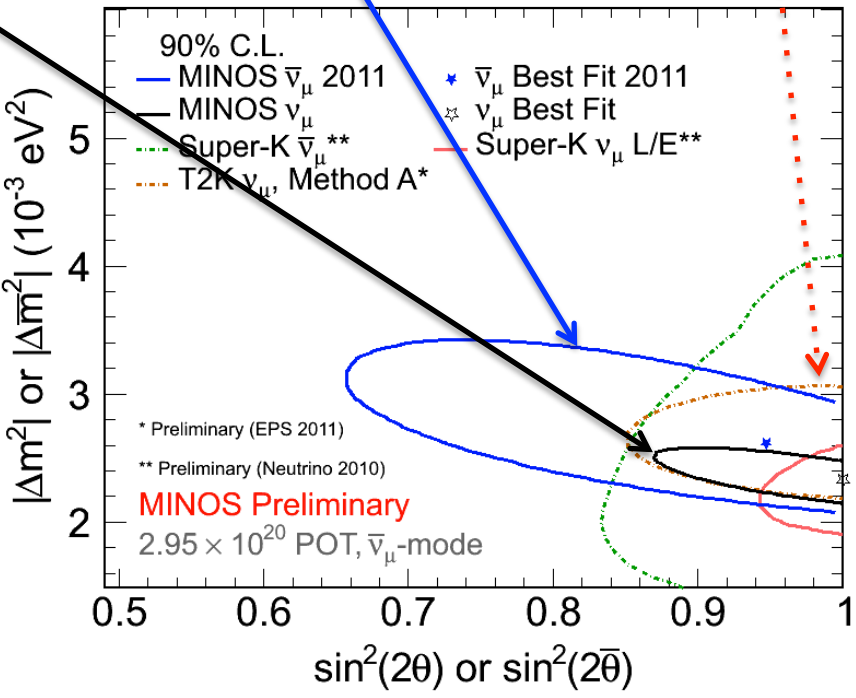






T2K achieves remarkable precision with small data set

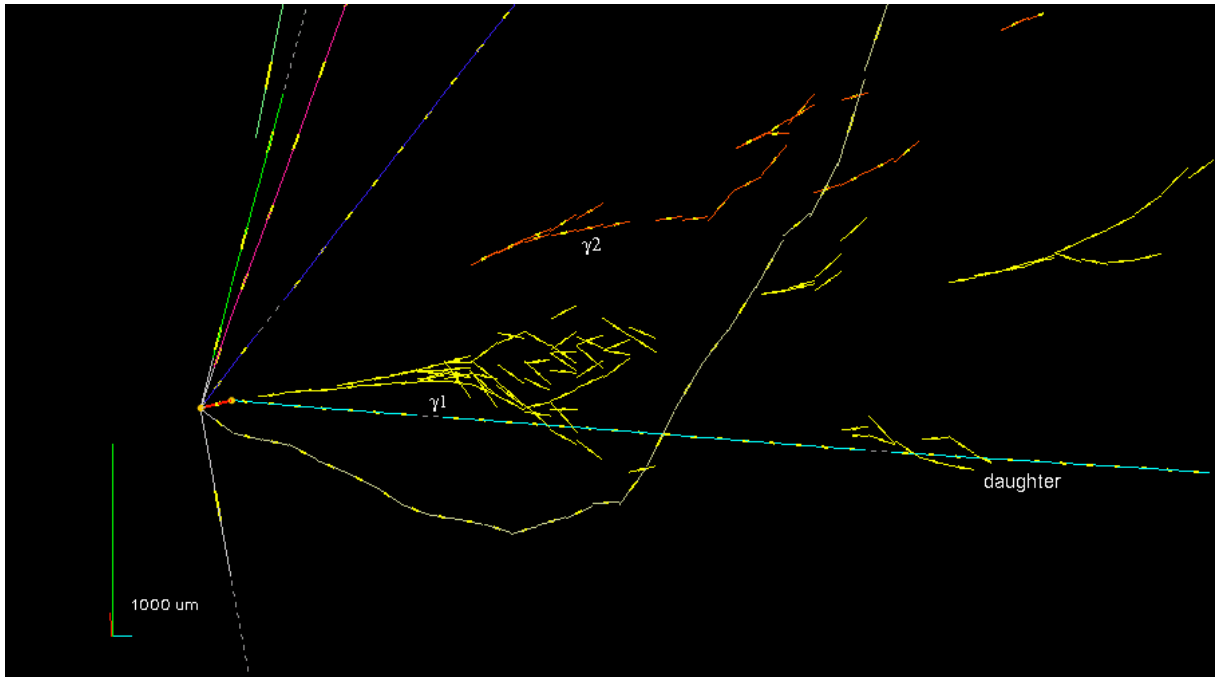




ν_τ appearance (Θ_{23})

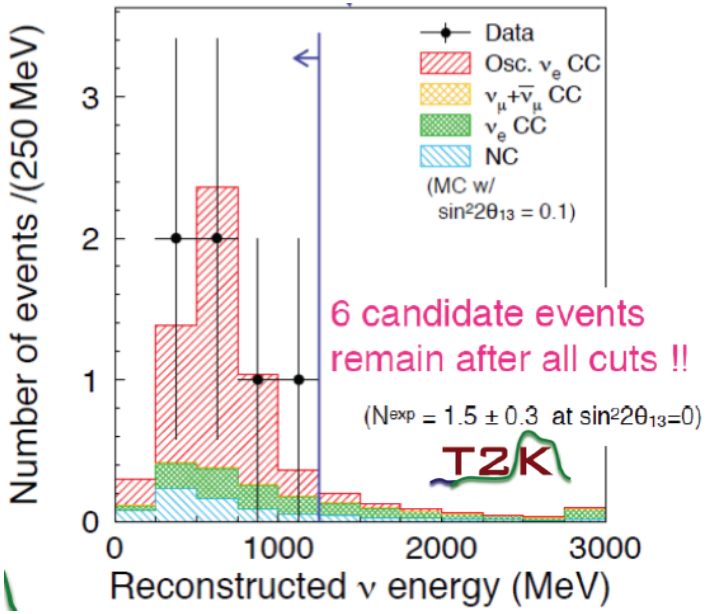
OPERA have observed one candidate event with 1.6 expected

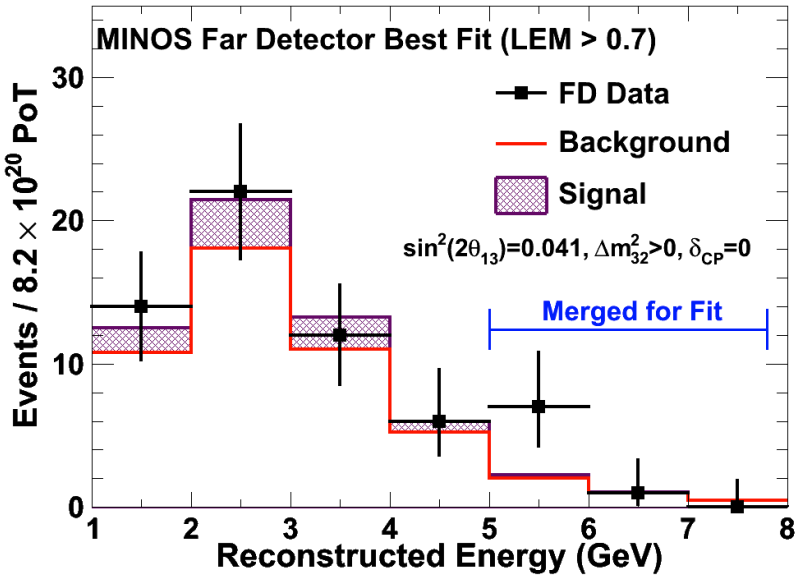
$\tau \rightarrow \rho \nu_\tau$
$\rho \rightarrow \pi\pi^0 \; (\pi^0 \rightarrow \gamma\gamma)$



Decay channel	Number of signal events expected for $Dm^2 = 2.5\times10^{-3}$ eV^2	
	22.5×10^{19} p.o.t.	Analysed sample
$\tau \rightarrow \mu$	1.79	0.39
$\tau \rightarrow e$	2.89	0.63
$\tau \rightarrow h$	2.25	0.49
$\tau \rightarrow 3h$	0.71	0.15
Total	7.63	1.65

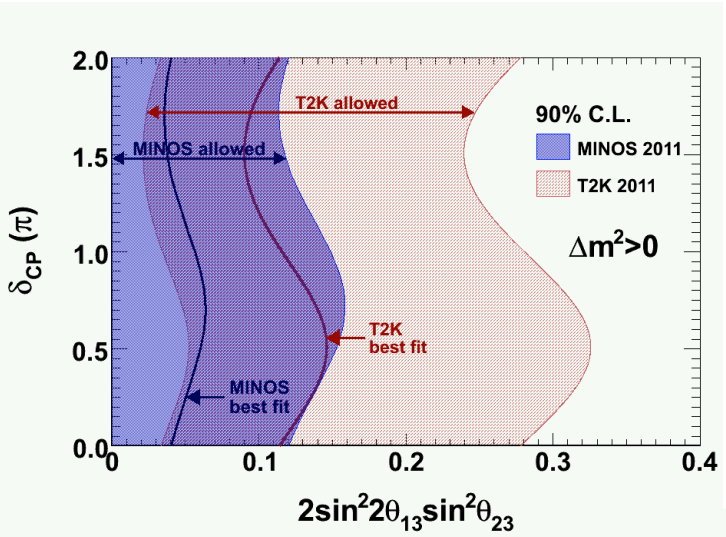
$\nu_\mu \rightarrow \nu_e$ appearance (Θ_{13})

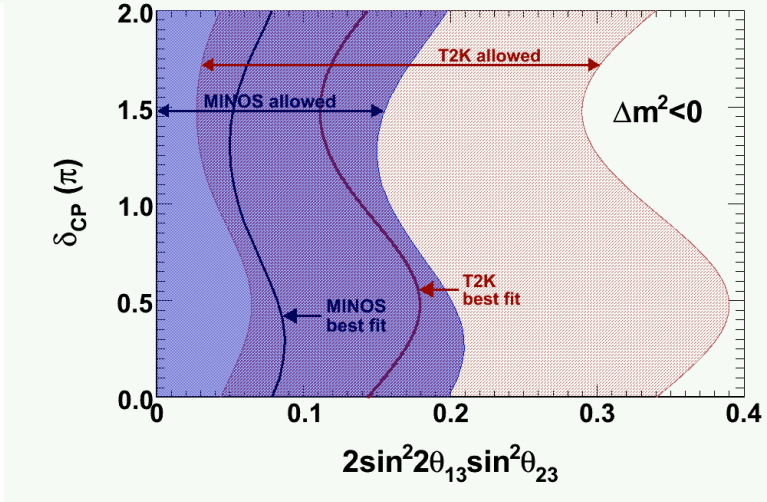




T2K: 2.5 sigma significance

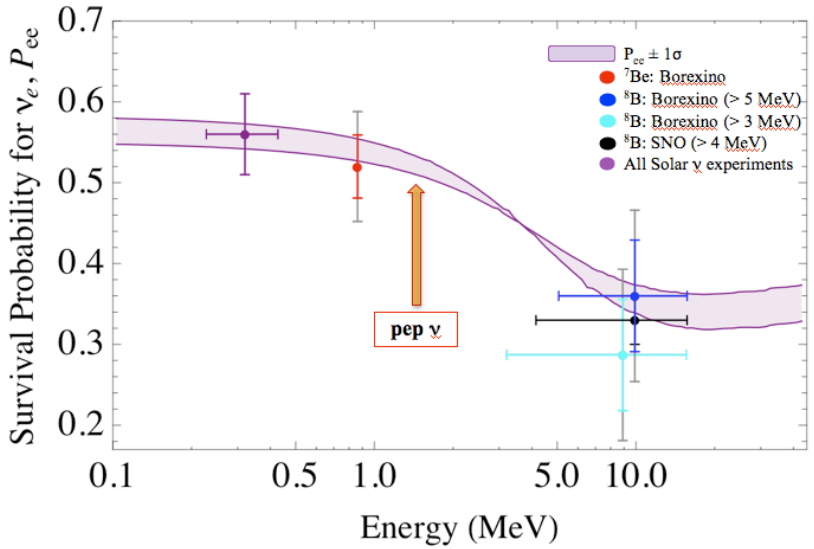
MINOS: 1.7 sigma



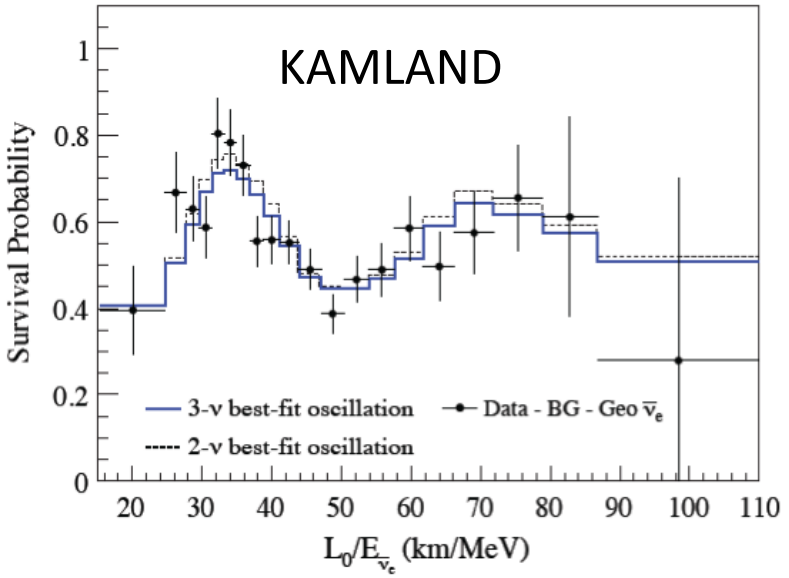


ν_e disappearance (Θ_{12})

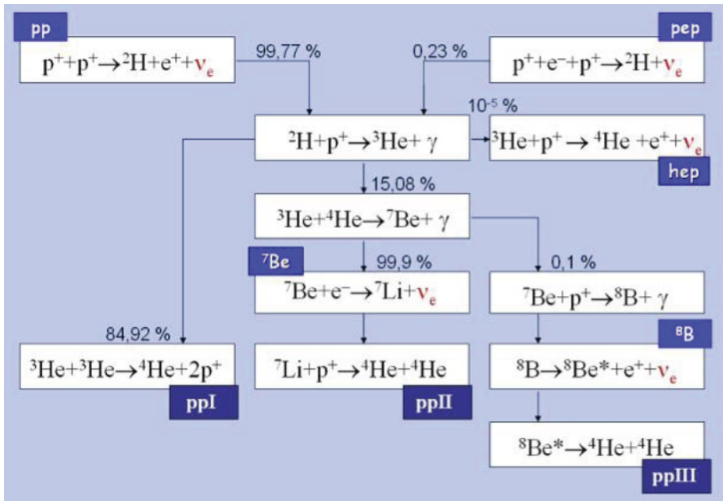
Solar

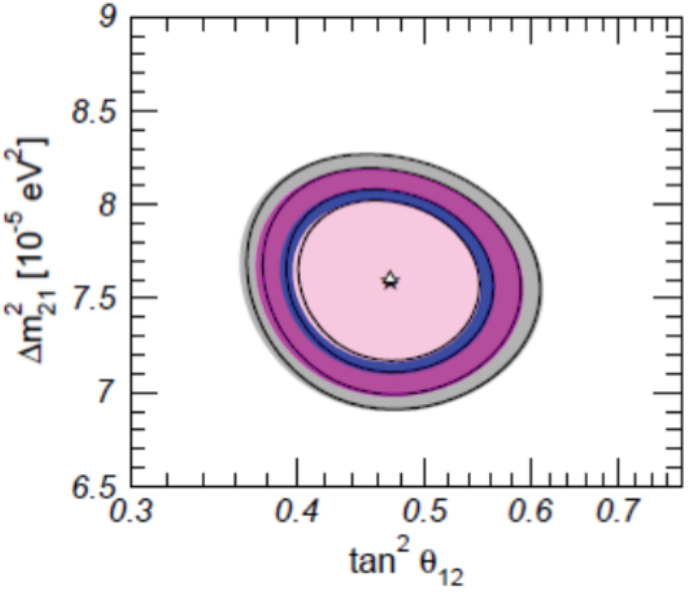


Reactor

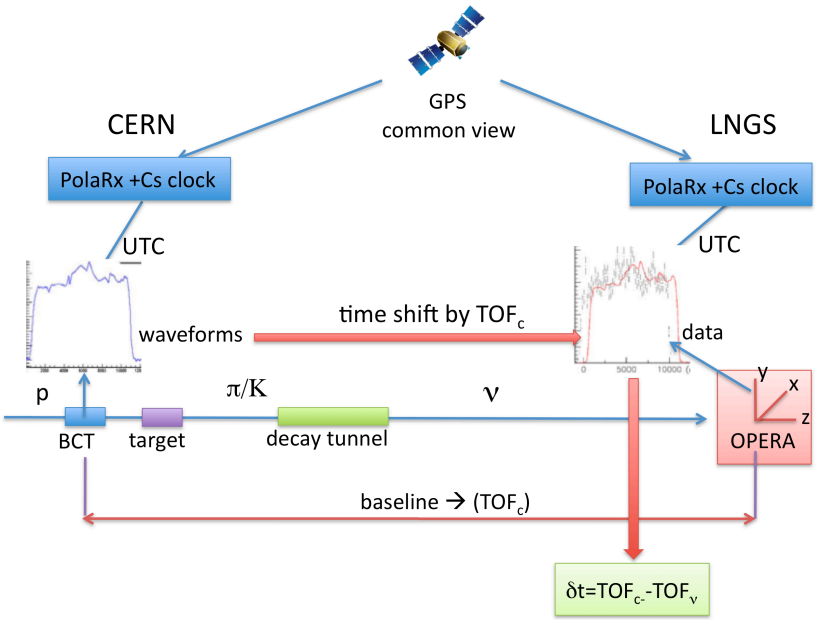


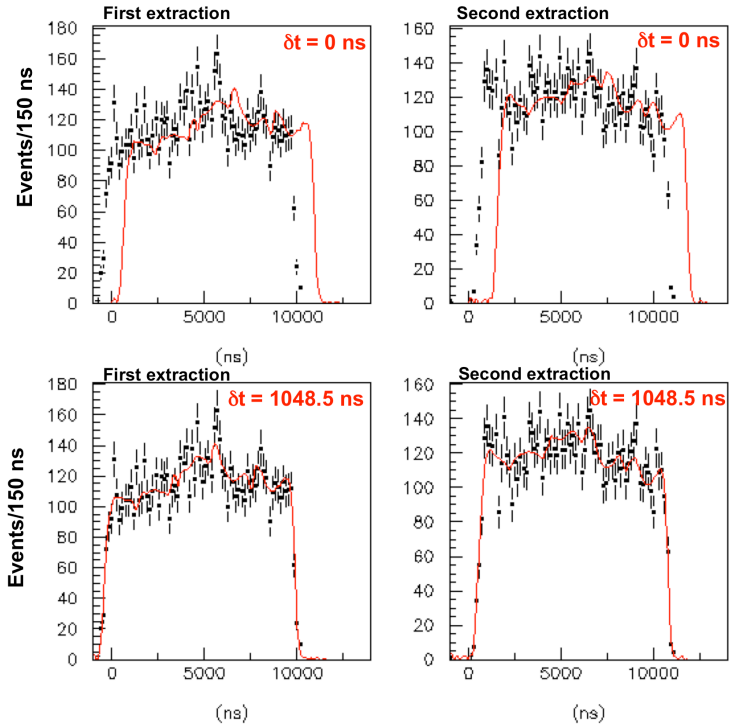
PP-chain





Supra-luminal neutrinos @ OPERA?





Time shift relative to assumption v=c

$$\delta t = (60.7 \pm 6.9\ (\text{stat.}) \pm 7.4\ (\text{sys.}))\ \text{ns}$$

Fractional discrepancy with assumption v=c

$$(v\text{-}c)/c = \delta t\ /(TOF'_c - \delta t) = (2.48 \pm 0.28\ (\text{stat.}) \pm 0.30\ (\text{sys.})) \times 10^{-5}$$

- Some results in non-accelerator-based astro-particle physics are covered in the talk by Hitoshi Murayama immediately following this one
  - and are the subject of a dedicated session on Tuesday

Tuesday, October 4, 2011

09:00 - 10:30 **Bridges of HEP with Dark Matter & Dark Energy**

Conveners: P. Drell, D. MacFarlane

09:00 **Theoretical Perspectives & Frontiers of Particle Astrophysics** *25'*
Speaker: Jihn Kim (Seoul, Asia)

09:25 **Prospects and Frontiers of Dark Matter** *25'*
Speaker: Priscilla Cushman (Minnesota, Americas)

09:50 **Prospects and Frontiers of Dark Energy** *25'*
Speaker: Ofer Lahav (UC London, Europe)

10:15 **Overall discussion 15'** *15'*

Conclusions, Outlook

- We live in exciting times!

- LHC 2011 has exceeded all expectations!
  - this is great news for our entire field
- Tevatron experiments have now ceased data taking
  - but have much data still to analyze

- Huge number of interesting measurements of which I have had time to describe but a few

- Many 3 sigma effects have come and gone over past 3 years, but some current hints are definitely worth watching:
  - LHC/Tevatron Higgs (discovery or exclusion)
  - Tevatron top A_{FB}
  - DØ like-sign muons A^{b}_{sl}
  - T2K/MINOS Θ_{13}
  - OPERA supra-luminal ν

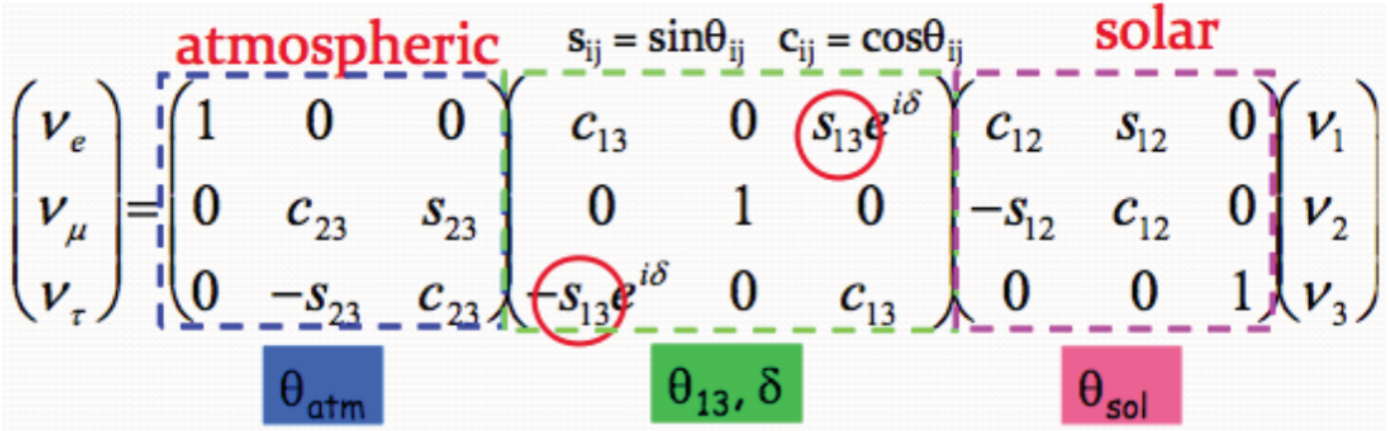
- Updates on these and a number of other new results should be available next year, e.g.:
  - Θ_{13} from reactors: near+far detectors

Backup slides

- a

Neutrino oscillations

$$|\nu_l\rangle = \sum_{i=1}^{3} U_{li} |\nu_i\rangle$$

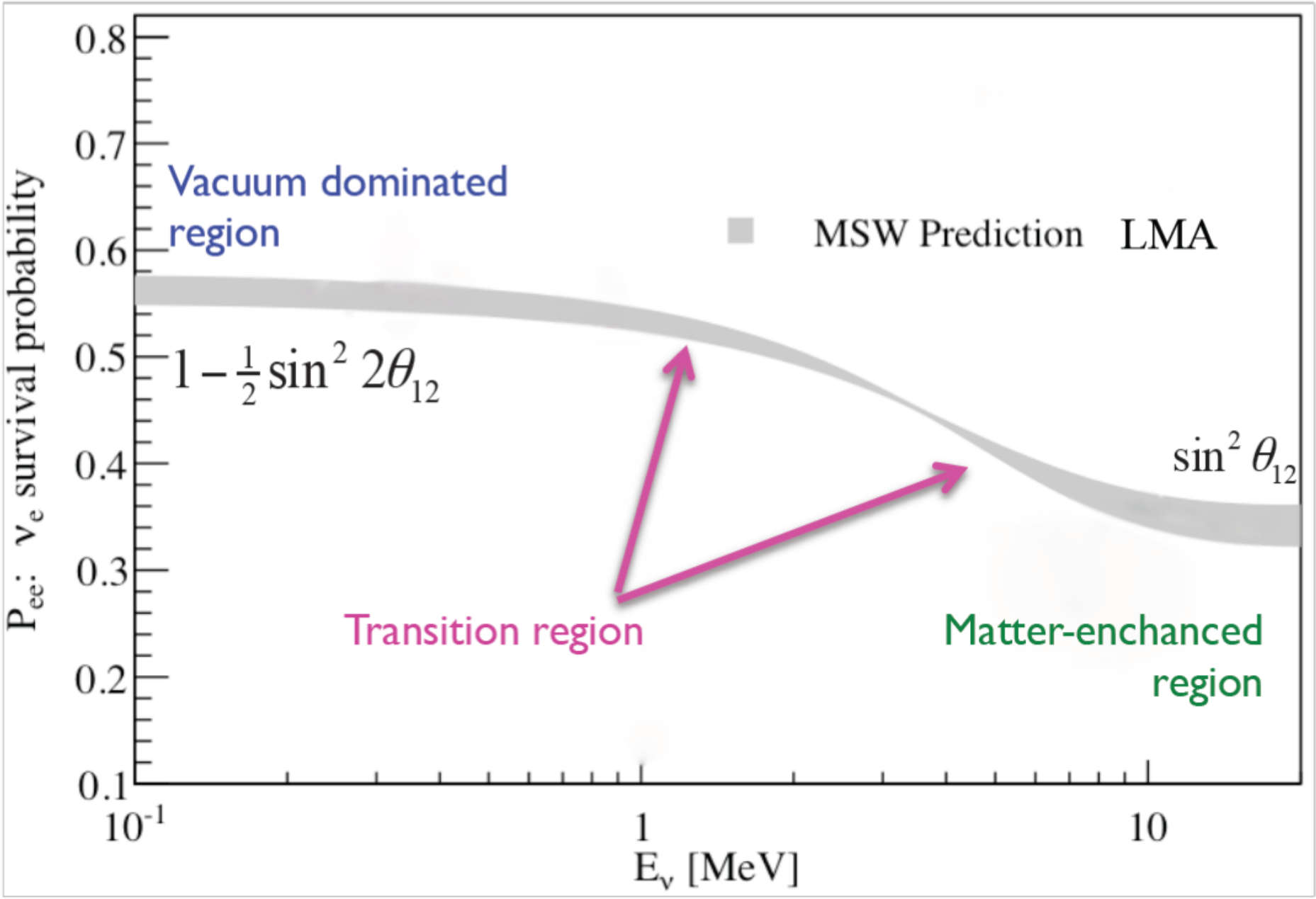


PMNS neutrino mixing matrix, analogous to CKM matrix for quarks

$\sin^2(2\theta_{12}) = 0.861^{+0.026}_{-0.022}$
$\Delta m^2_{21} = (7.59 \text{+-} 0.21) \times 10^{-5}$ eV^2
$\sin^2(2\theta_{23}) > 0.92$ [i]
$\Delta m^2_{32} = (2.43 \pm 0.13) \times 10^{-3}$ eV^2
$\sin^2(2\theta_{13}) < 0.15$, CL = 90%

Solar
reactor LBL (KamLAND)
Atmospheric
accelerator LBL (MINOS, T2K)
reactor SBL (Chooz)

$$P_{ee} = 1 - \sin^2 2\theta \sin^2 (\Delta m^2 L / 4E_\nu)$$


0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
P_{ee}: ν_e survival probability
Vacuum dominated region
MSW Prediction LMA
$1-\frac{1}{2}\sin^2 2\theta_{12}$
$\sin^2\theta_{12}$
Transition region
Matter-enchanced region
10^{-1}
1
10
E_ν [MeV]