LHC Startup

XVI International Workshop on Deep-Inelastic Scattering

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U. Wisconsin - Madison

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Outline:

Review of LHC, ATLAS, CMS, LHCb, ALICE

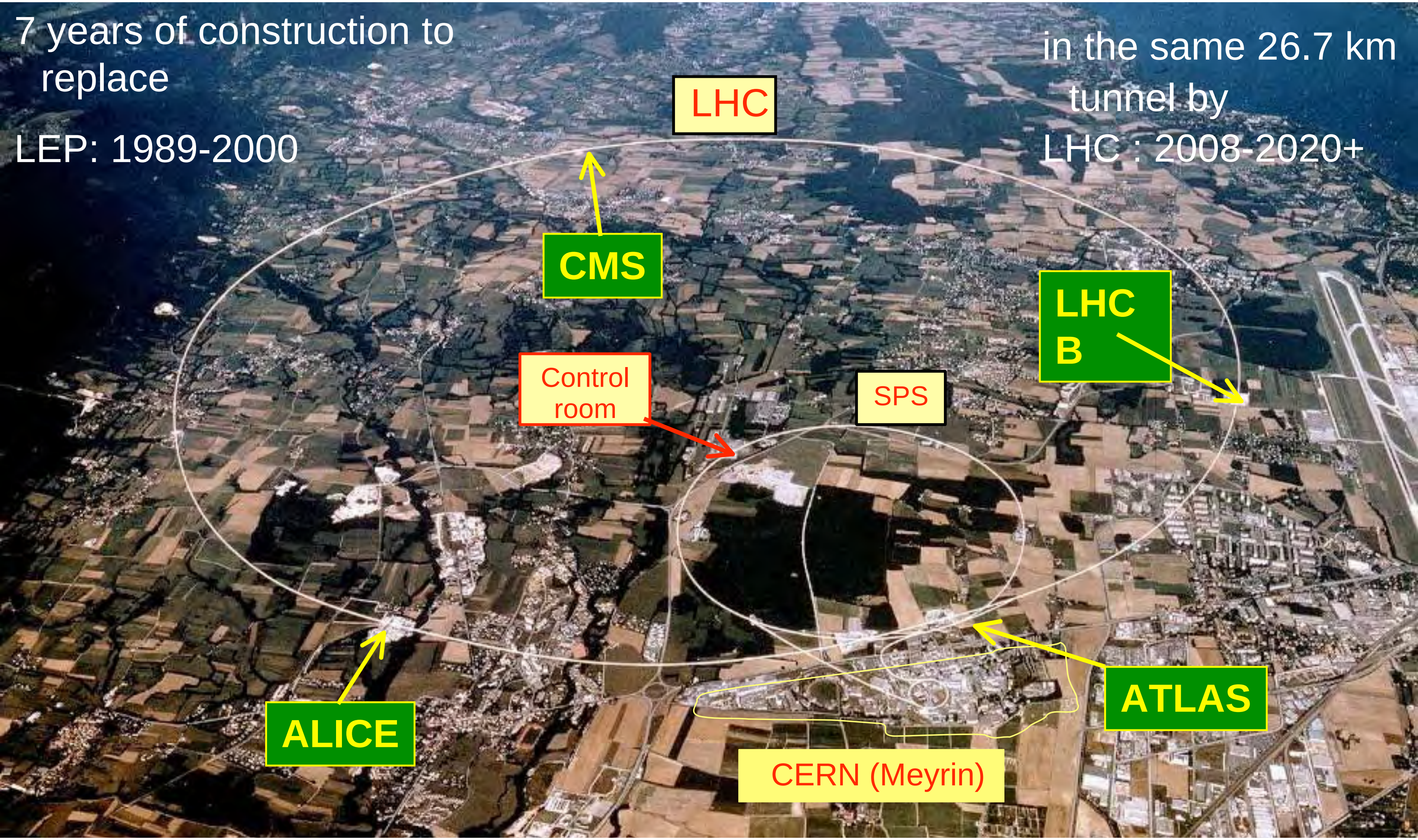
Startup scenario

Physics with 1, 10, 100 pb^{-1}

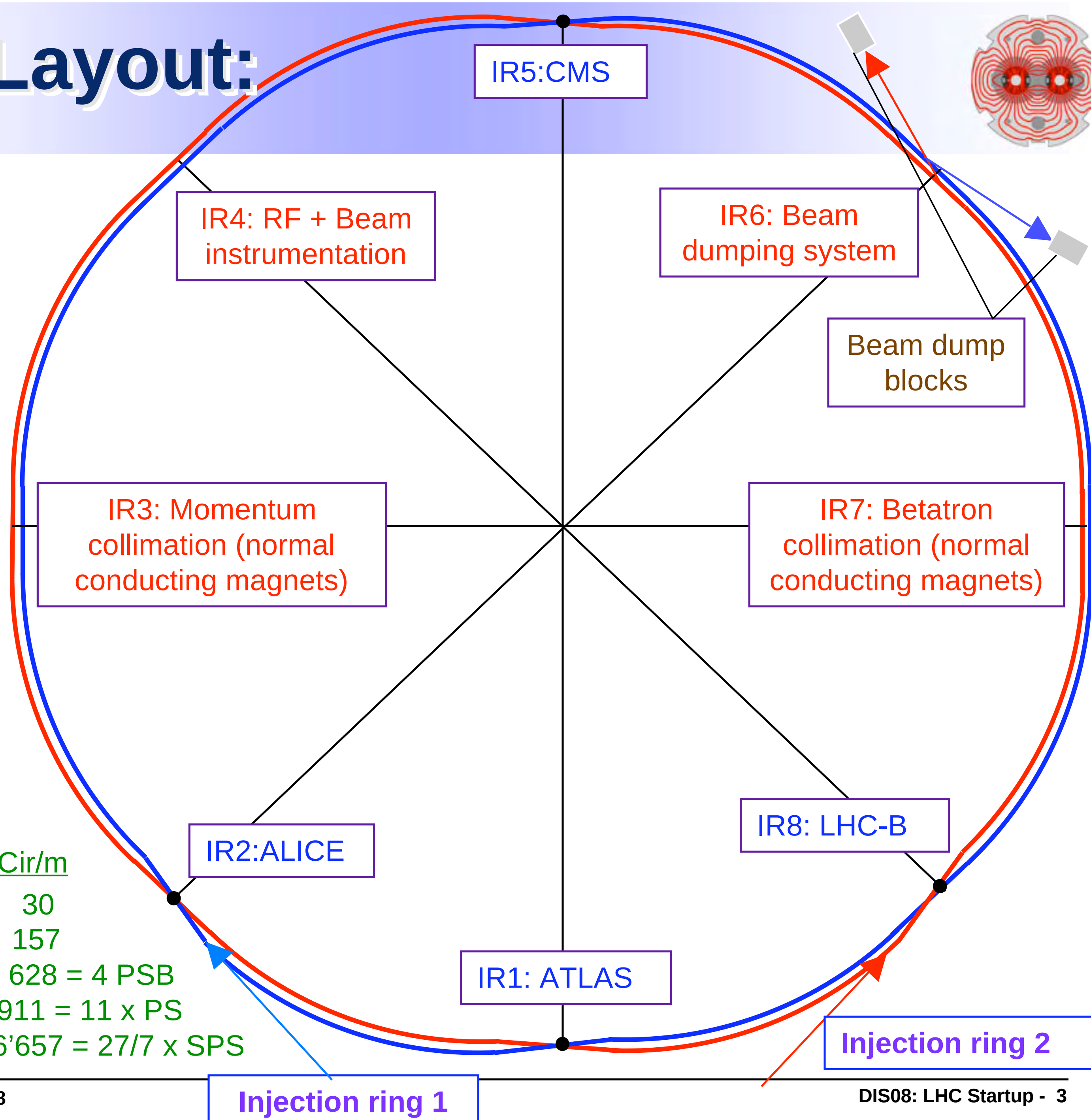
This talk is available on:

http://www.hep.wisc.edu/wsmith/cms/doc08/smith_lhcstart_dis08_apr08.pdf

The CERN & LHC Complex



LHC Layout:



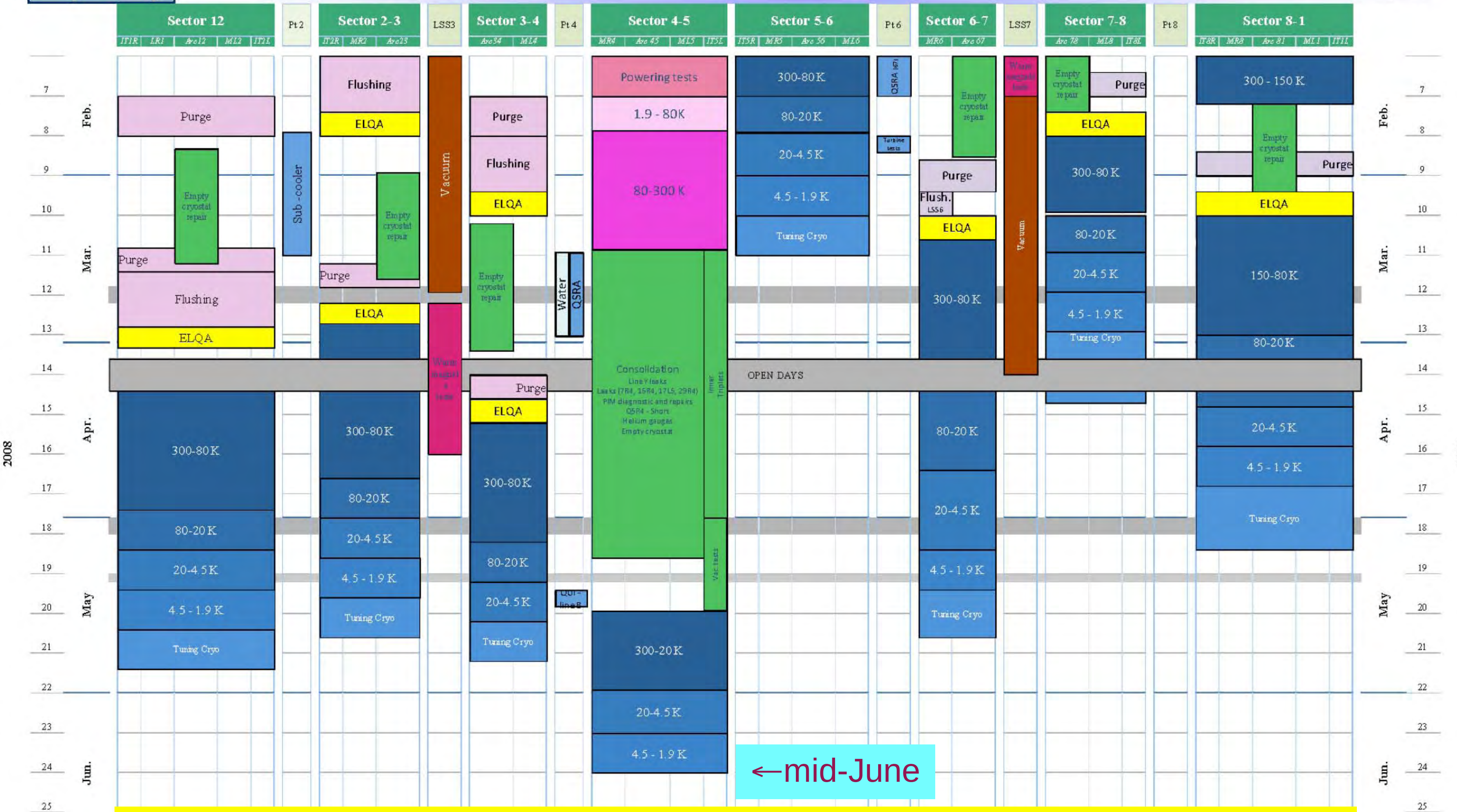
Details:

- 8 arcs.
- 8 long straight sections (insertions), ~ 700 m long.
- beam 1 : clockwise
- beam 2 : counter-clockwise
- The beams exchange their positions (inside/outside) in 4 points to ensure that both rings have the same circumference !

In total > 50 km of beam lines

	Top energy/GeV	Cir/m
Linac	0.12	30
PSB	1.4	157
CPS	26	628 = 4 PSB
SPS	450	6'911 = 11 x PS
LHC	7000	26'657 = 27/7 x SPS

LHC Schedule

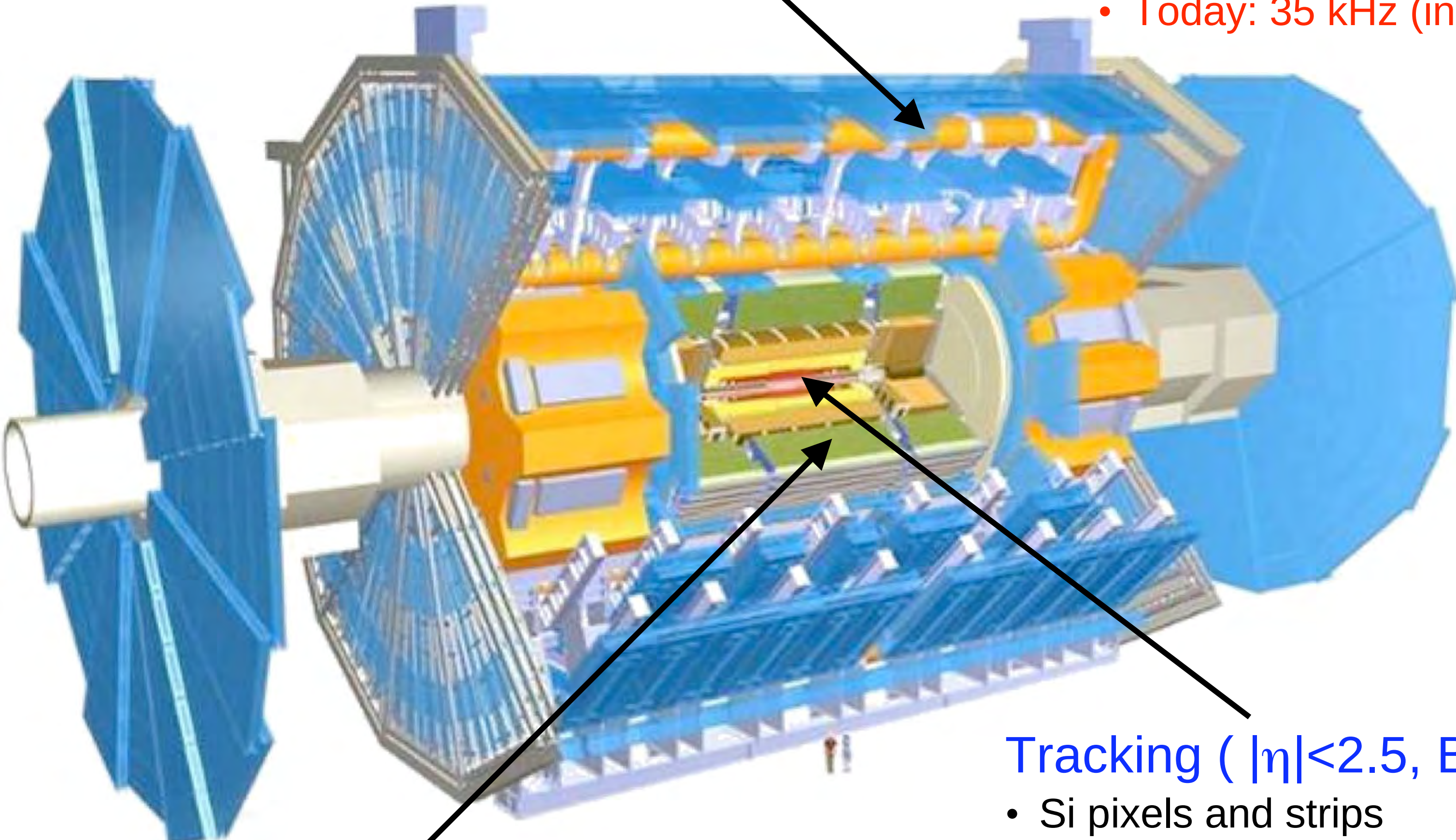


First circulation of beam starts ~ 1 month after cool down complete
LHC will start at 10 TeV & operate at 14 TeV after winter shutdown

ATLAS Detector Design

Muon Spectrometer ($|\eta|<2.7$)
- air-core toroids with muon chambers

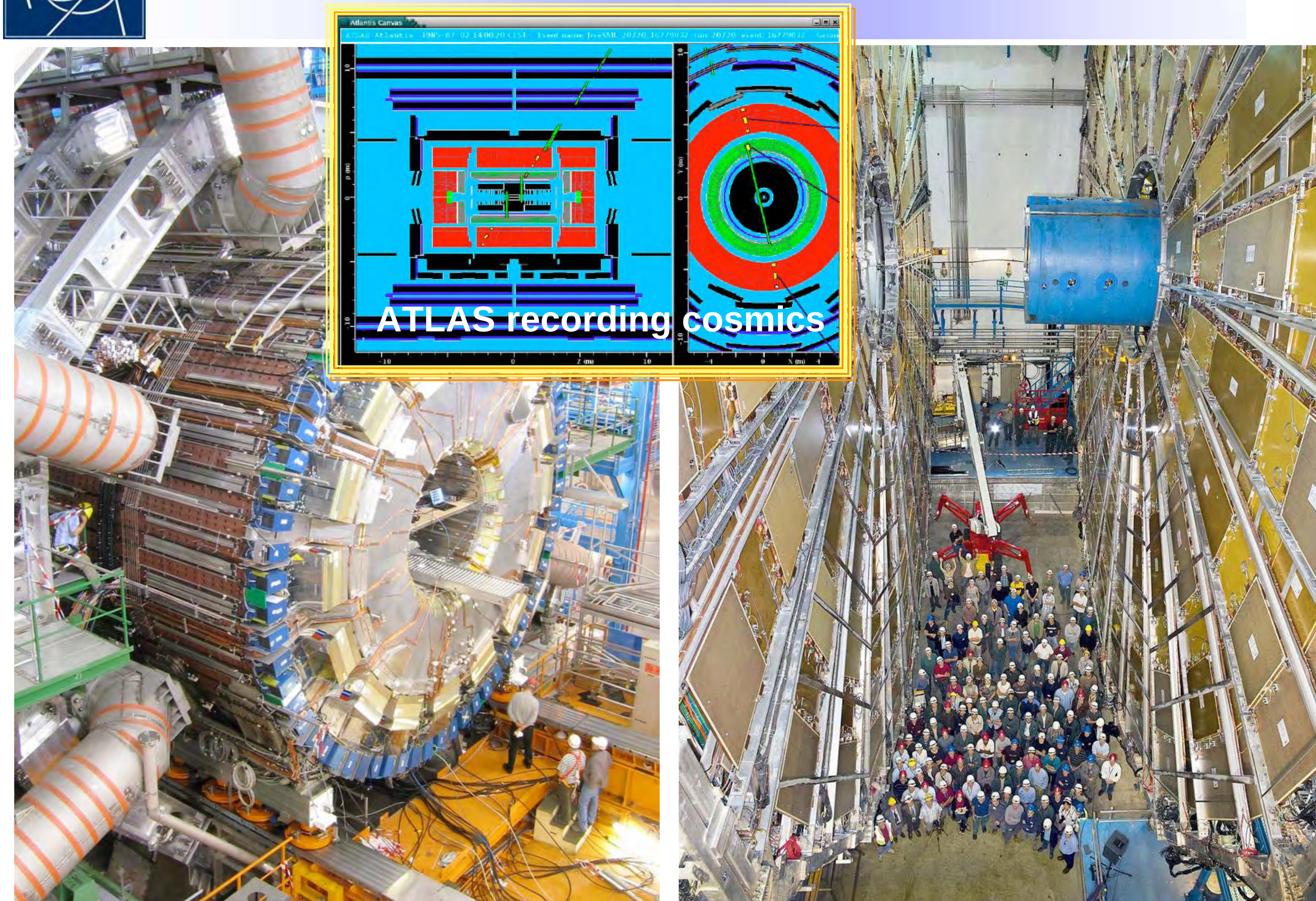
Level-1 Trigger Output
- Today: 35 kHz (instead of 75)



Tracking ($|\eta|<2.5$, B=2T)
- Si pixels and strips
- TRD (e/π separation)
- Today: TRT $|\eta| < 2$ (instead of 2.4)

Calorimetry ($|\eta|<5$)
- EM : Pb-LAr
- HAD : Fe/scintillator (central), Cu/W-Lar (fwd)

ATLAS in 2007



CMS Detector Design

Superconducting Coil, 4 Tesla

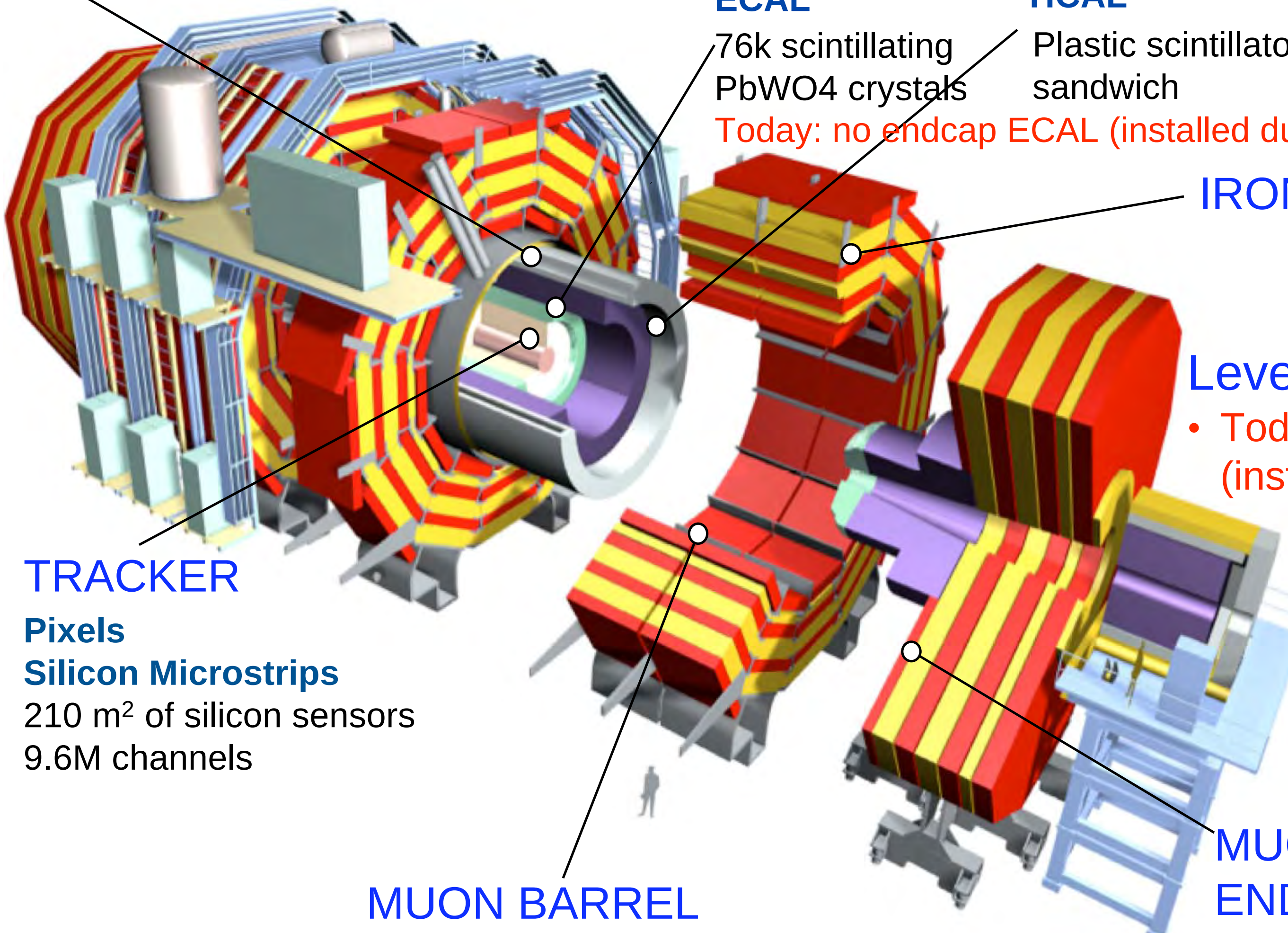
CALORIMETERS

ECAL
76k scintillating PbWO4 crystals

HCAL
Plastic scintillator/brass sandwich

Today: no endcap ECAL (installed during 1st shutdown)

IRON YOKE



Level-1 Trigger Output
- Today: 50 kHz (instead of 100)

TRACKER

Pixels
Silicon Microstrips
210 m^2 of silicon sensors
9.6M channels

Today:
RPC $|\eta| < 1.6$ instead of 2.1
& 4th endcap layer missing

MUON BARREL

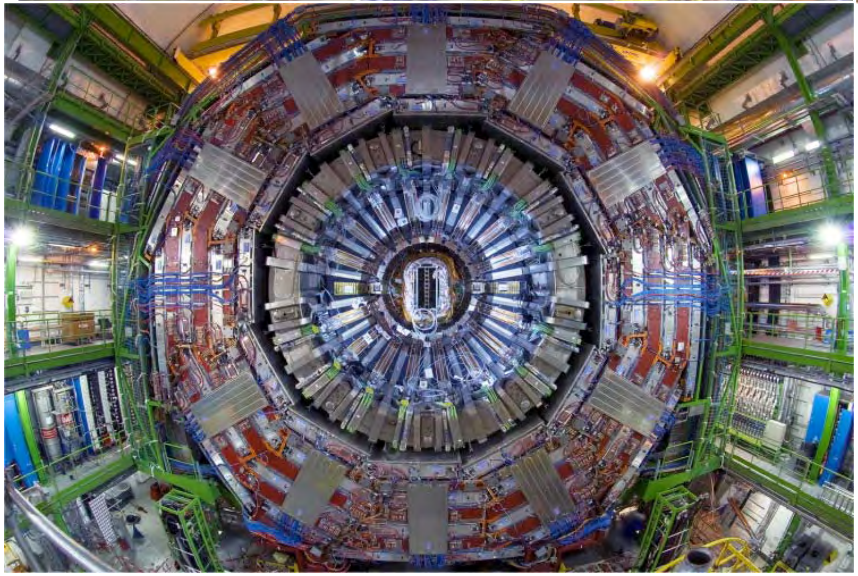
Drift Tube Chambers (DT)

Resistive Plate Chambers (RPC)

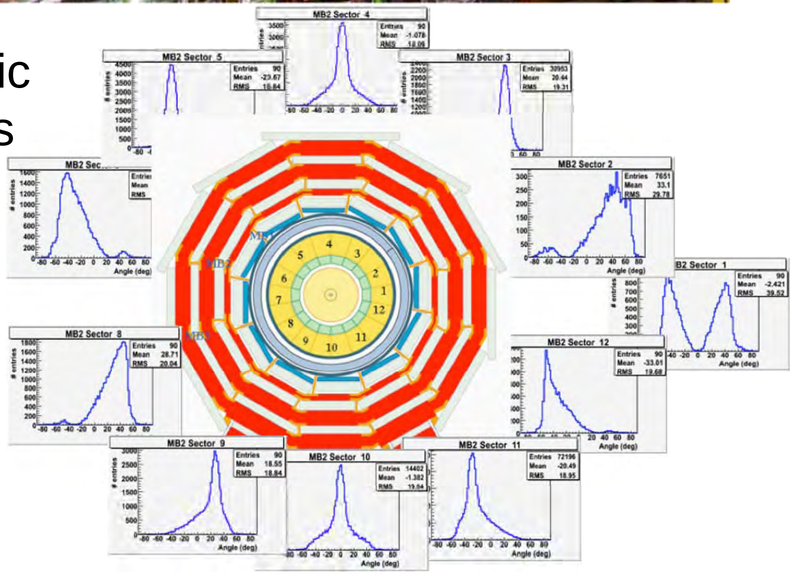
MUON ENDCAPS

Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

CMS in 2007



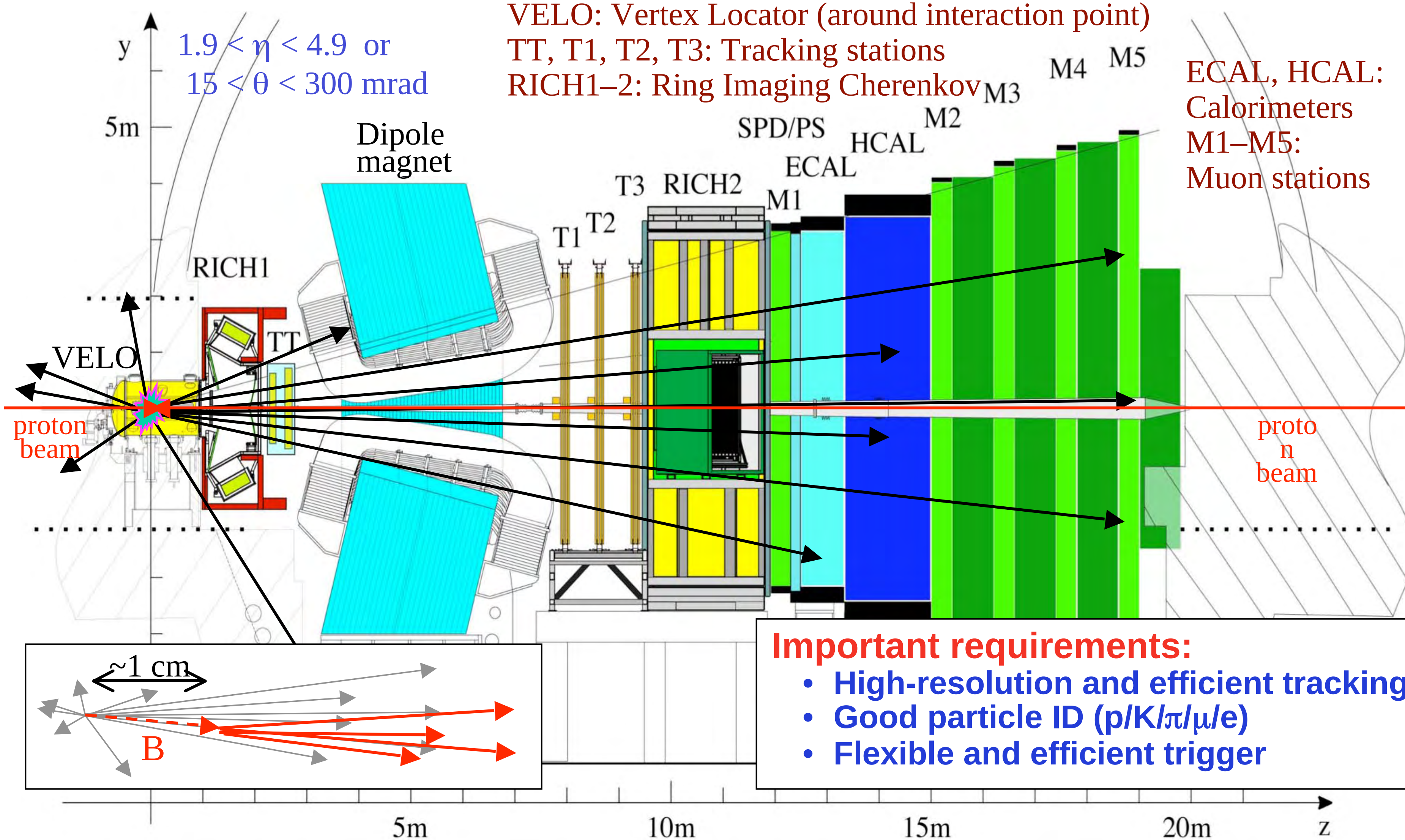
Cosmic muons thru drift tubes



LHCb Design

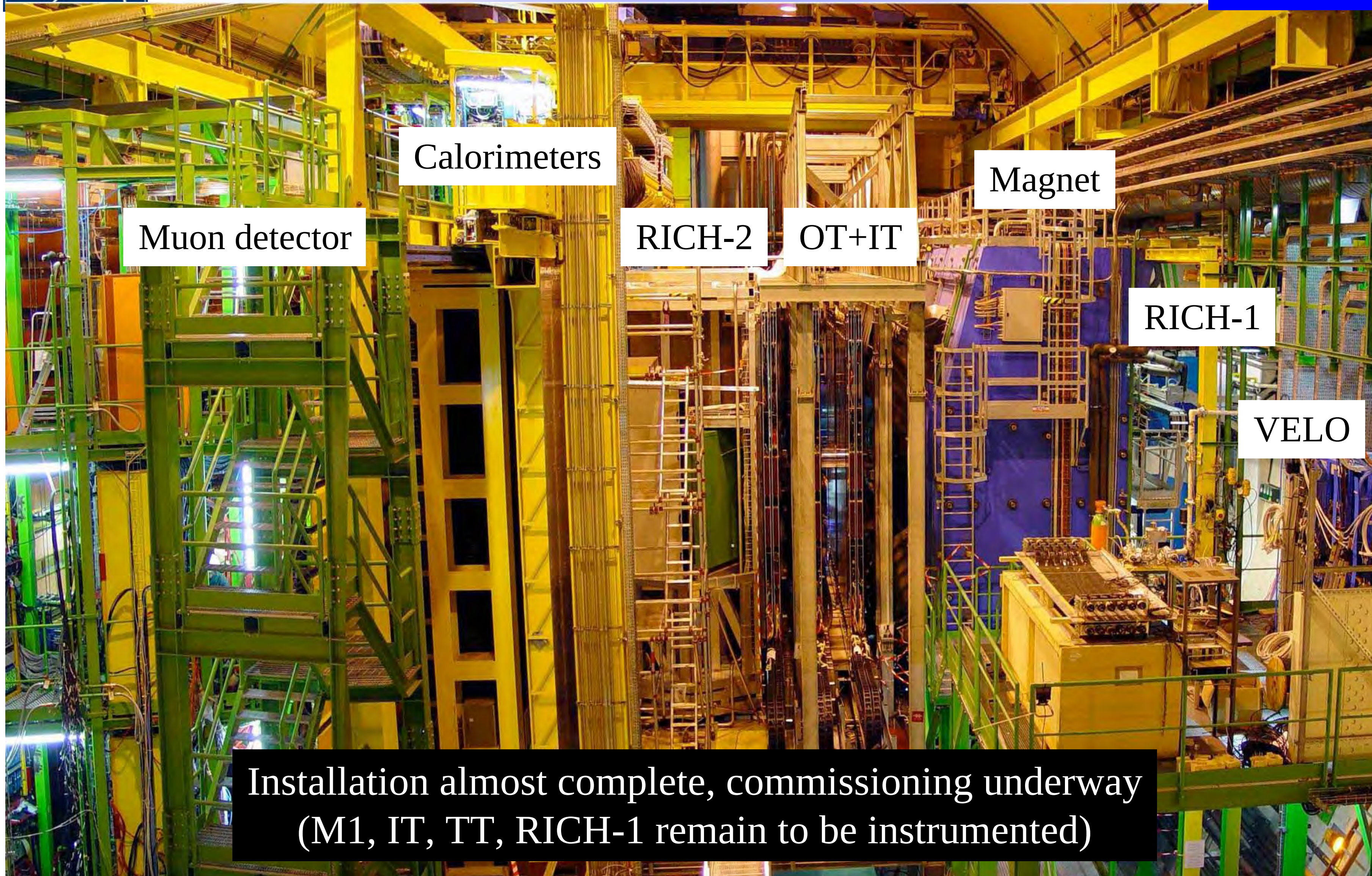
VELO: Vertex Locator (around interaction point)
TT, T1, T2, T3: Tracking stations
RICH1–2: Ring Imaging Cherenkov

ECAL, HCAL: Calorimeters
M1–M5: Muon stations



Important requirements:
- **High-resolution and efficient tracking**
- **Good particle ID (p/K/π/μ/e)**
- **Flexible and efficient trigger**

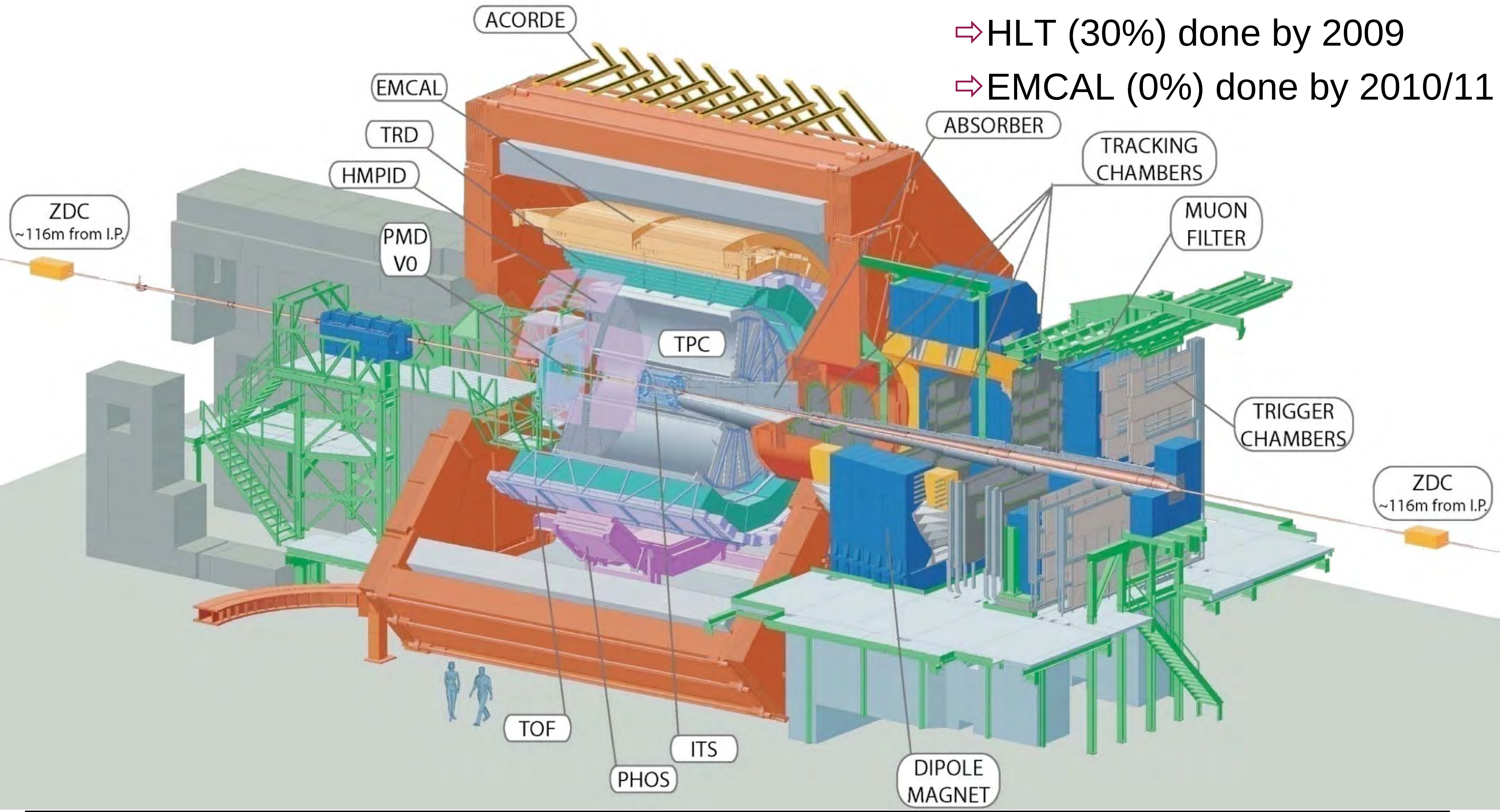
LHCb in 2007



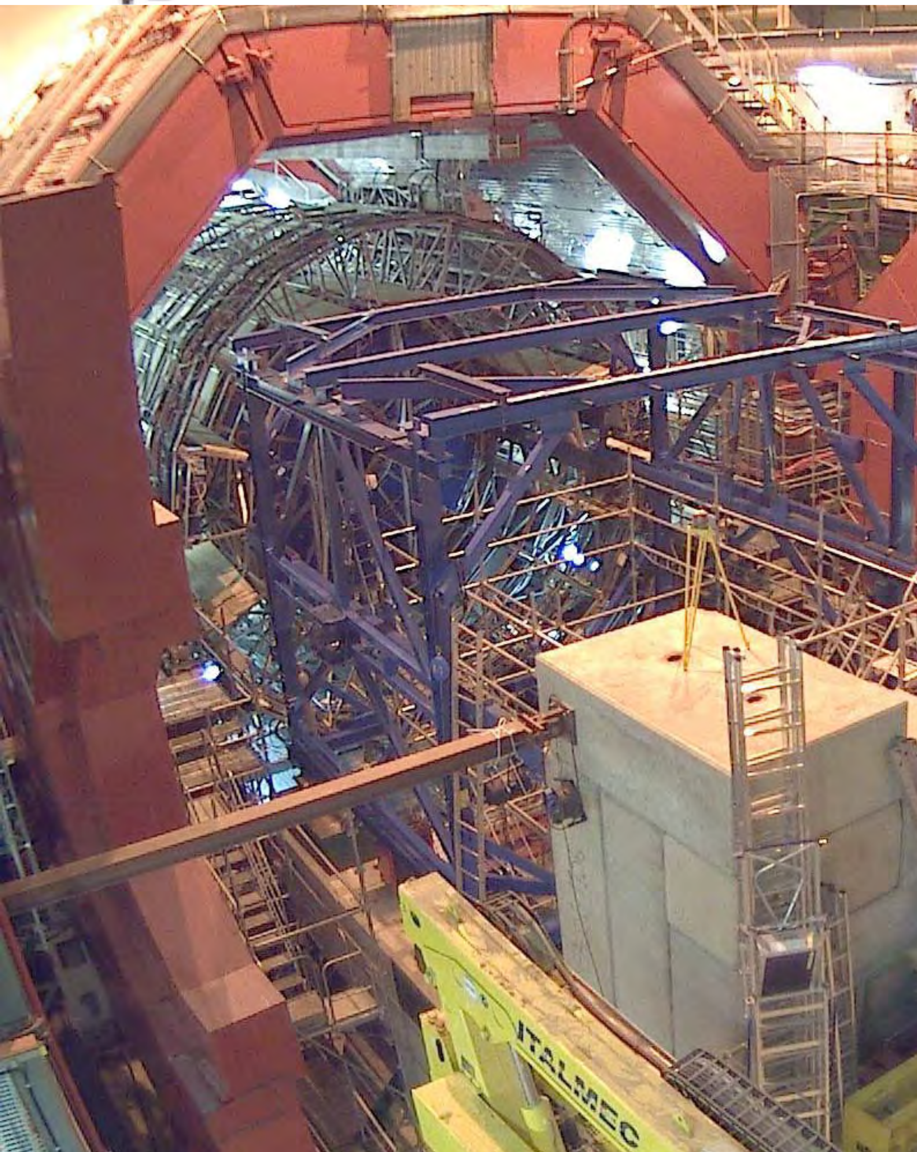
Calorimeters
Magnet
Muon detector
RICH-2
OT+IT
RICH-1
VELO
Installation almost complete, commissioning underway
(M1, IT, TT, RICH-1 remain to be instrumented)

ALICE Design

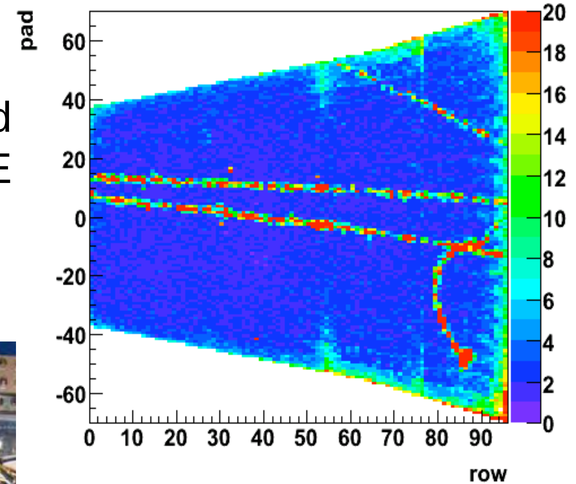
Partially Incomplete:
- ⇨TRD (25%) done by 2009
- ⇨PHOS (60%) done by 2010
- ⇨HLT (30%) done by 2009
- ⇨EMCAL (0%) done by 2010/11

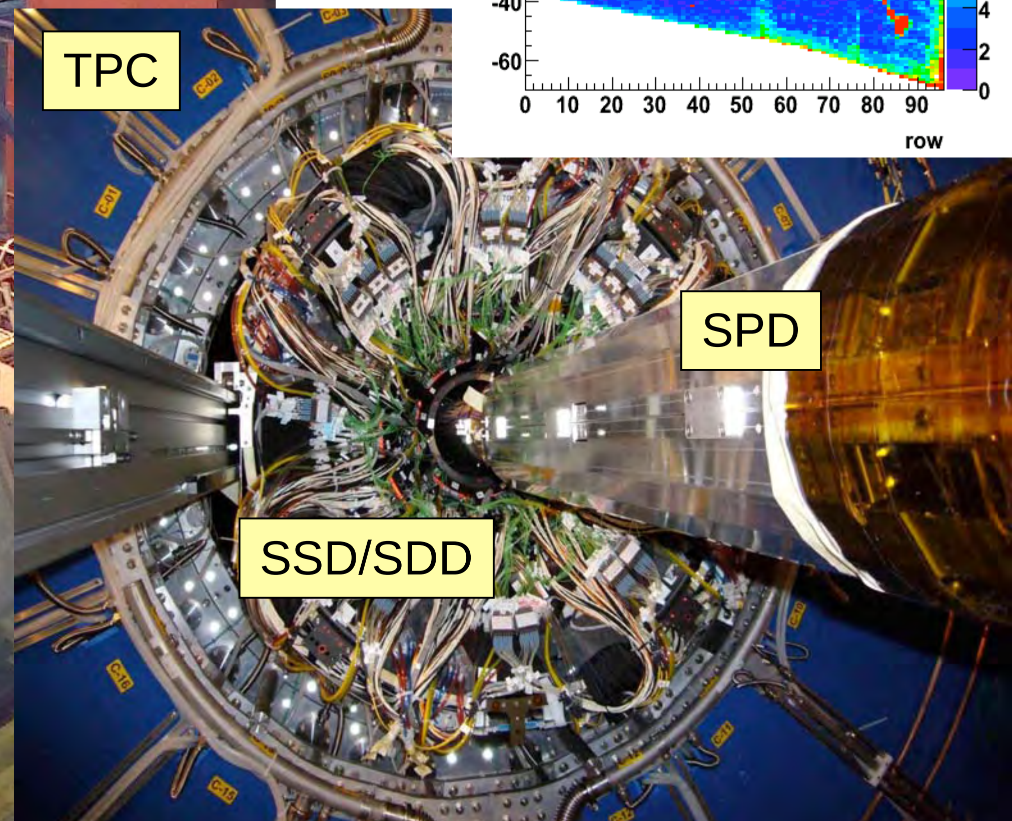


ALICE in 2007



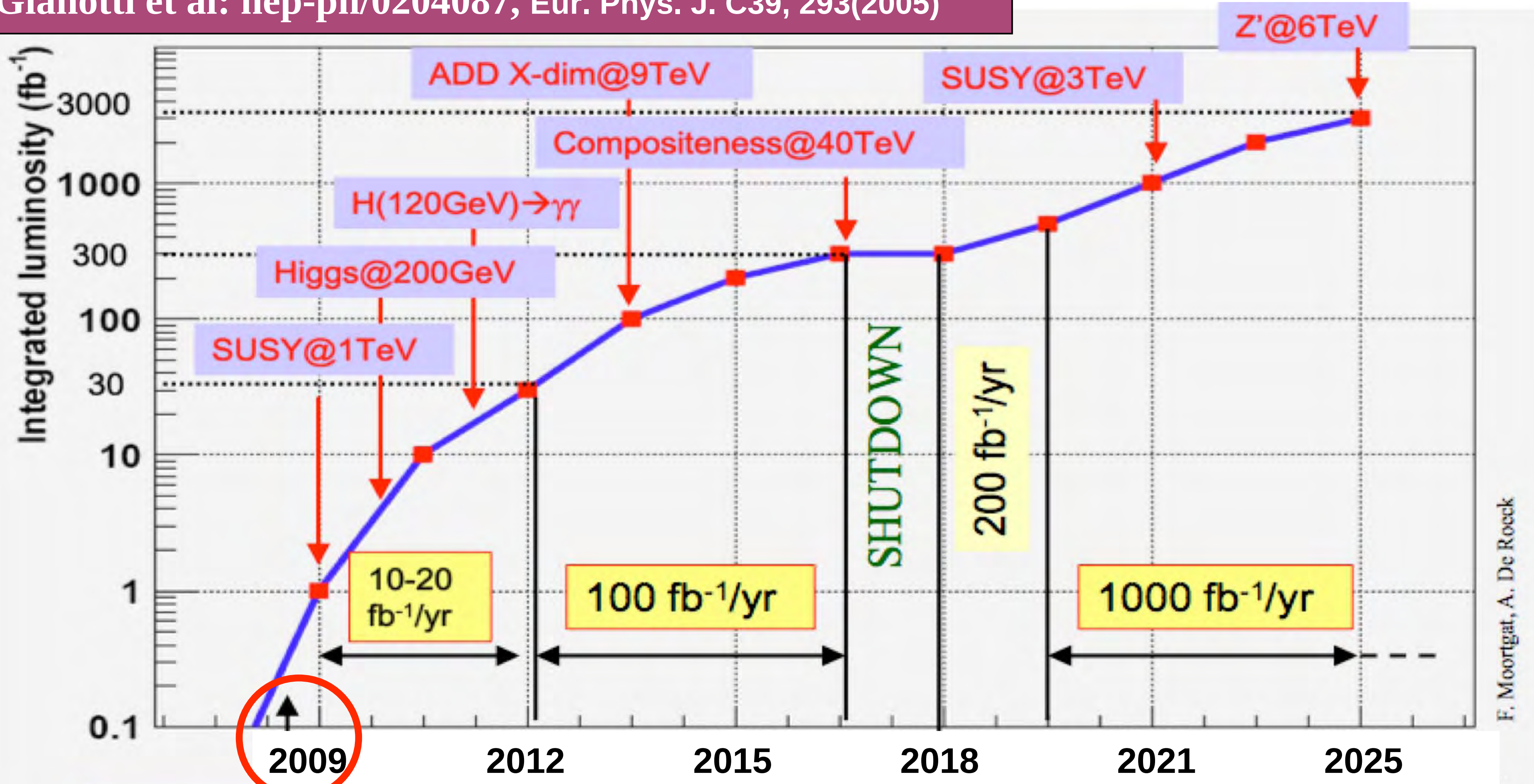
Comics recorded in ALICE TPC





ATLAS,CMS physics evolution

De Roeck, Ellis, Gianotti: hep-ph/0112004
Gianotti et al: hep-ph/0204087, Eur. Phys. J. C39, 293(2005)



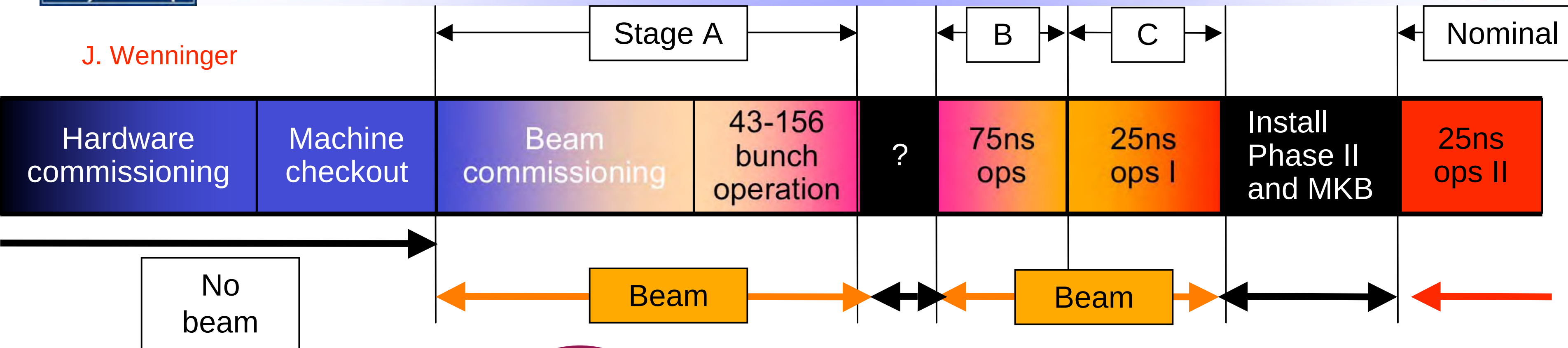
Start Luminosity buildup

"A journey of a thousand miles begins with a single step" - Lao-tzu

Timescale adjusted

Luminosity Buildup

J. Wenninger



Parameter	Phase A	Phase B	Phase C	Nominal
k / no. bunches	43-156	936	2808	2808
Bunch spacing (ns)	2021-566	75	25	25
N (10^{11} protons)	0.4-0.9	0.4-0.9	0.5	1.15
Crossing angle (μrad)	0	250	280	280
$\sqrt{(\beta^*/\beta^*_{nom})}$	2	$\sqrt{2}$	1	1
σ* (μm, IR1&5)	32	22	16	16
L ($cm^{-2}s^{-1}$)	6×10^{30}-10^{32}	10^{32}-10^{33}	$(1\text{-}2) \times 10^{33}$	10^{34}
∫Ldt (my guess @ 6×10^6s pp/year)	< 100 pb^{-1}	< 1 fb^{-1}	< 10 fb^{-1}	60 fb^{-1}/yr

Phase A Luminosities

Approx 30 days of beam time to establish first collisions

1 to N to 43 to 156 bunches per beam

Estimate no less than 1 week per step below

May take considerably longer…

Bunches	β*	I_b	Lumi	Pileup	MB rate	∫Ldt/wk
1 x 1	18	10^{10}	10^{27}	Low	55 Hz	
43 x 43	18	3×10^{10}	3.8×10^{29}	0.06	20 kHz	
43 x 43	4	3×10^{10}	1.7×10^{30}	0.28	60 kHz	~0.1 pb^{-1}
43 x 43	2	4×10^{10}	6.1×10^{30}	0.99	200 kHz	
156 x 156	4	4×10^{10}	1.1×10^{31}	0.50	400 kHz	~1 pb^{-1}
156 x 156	4	9×10^{10}	5.6×10^{31}	2.3	2 MHz	
156 x 156	2	9×10^{10}	1.1×10^{32}	5.0	4 MHz	~10 pb^{-1}

What do you get per 1 pb^{-1}?

Note: all rates, results, etc. shown in this talk are for √s=14 TeV, not 10 TeV

Channel	# of Events
W -> μν	7000
Z -> μμ	1100
t tbar -> μ + X	80
QCD jets P_T>150 GeV	1000 (for 10% of trigger bandwith)
Minimum bias	Trigger limited
gluino-gluino, M~ 1TeV	1-10

scaled from table in hep-ph/0504221
Using ATLAS trigger

What do you do with it? ⇒

"and the dove came back to him in the evening and lo, in her mouth a freshly plucked olive leaf" -- Genesis 8:11

Calibration & Alignment

Starting Point	Expected performance day-1		Physics samples to improve (examples)
	ATLAS	CMS	
ECAL uniformity	1-2%	4%	Isolated electrons, $Z \rightarrow ee$
e/γ E-scale	~ 2 %	~ 2 %	$Z \rightarrow ee$
HCAL uniformity	~ 3 %	~ 2-3 %	Single pions, QCD jets
Jet E-scale	< 10%	< 10%	γ/Z + 1j, $W \rightarrow jj$ in tt events
Tracking alignment	10-200 μm in $R\phi$	20-200 μm in $R\phi$	Generic tracks, isolated μ, $Z \rightarrow \mu\mu$

Use the early data to improve:

- ECAL, HCAL: intercalibration w/azimuthal symmetry
  - minimum bias
- ECAL: π^0 calibration, then electrons from $Z \rightarrow ee$
- Jet Energy Scale: di-jet balancing, γ/Z+jet, $W \rightarrow jj$ in tt events
- Inner Tracking & Muon Alignment: $Z \rightarrow \mu\mu$

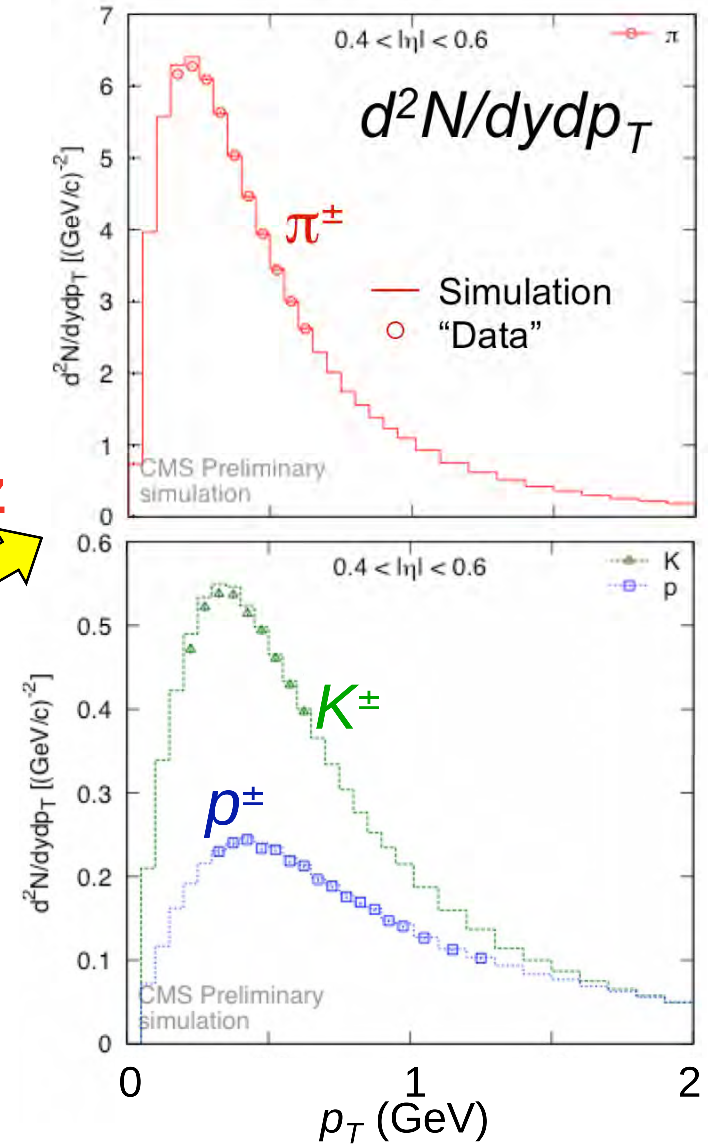
Charged-Hadron Spectra

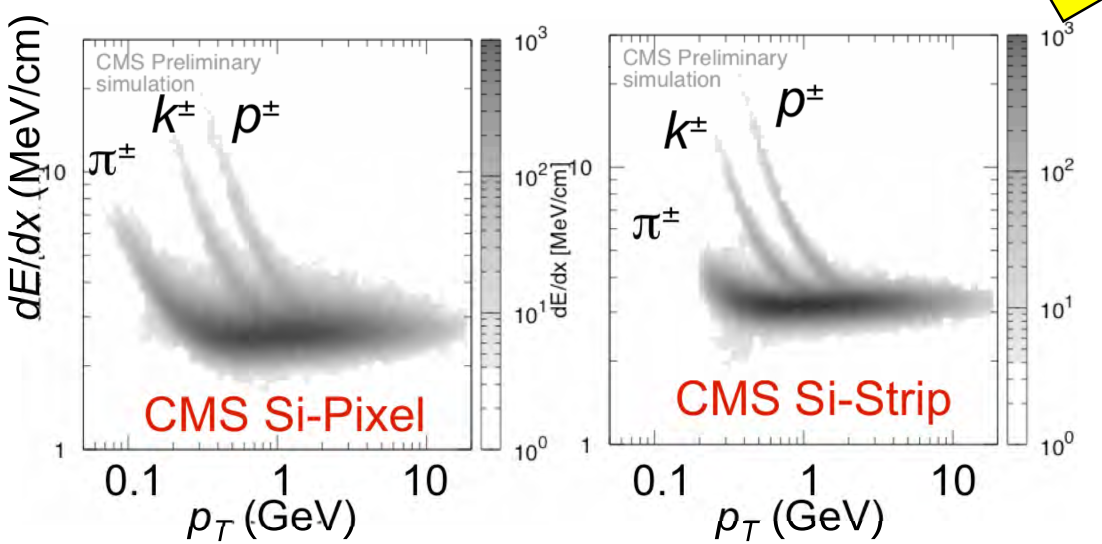
One of the first measurements to be done: charged-hadron spectrum

- **Never before explored at $\sqrt{s}$ > 2 TeV**
- **Important tool for calibration & understanding of detector response**

Min-bias and/or Zero-bias trigger

Statistics: ~ 1 month (at 70%) with 1Hz allocated trigger bandwidth

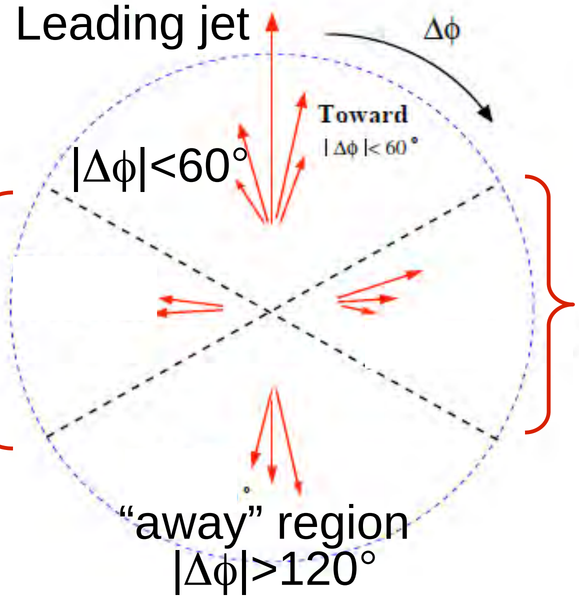




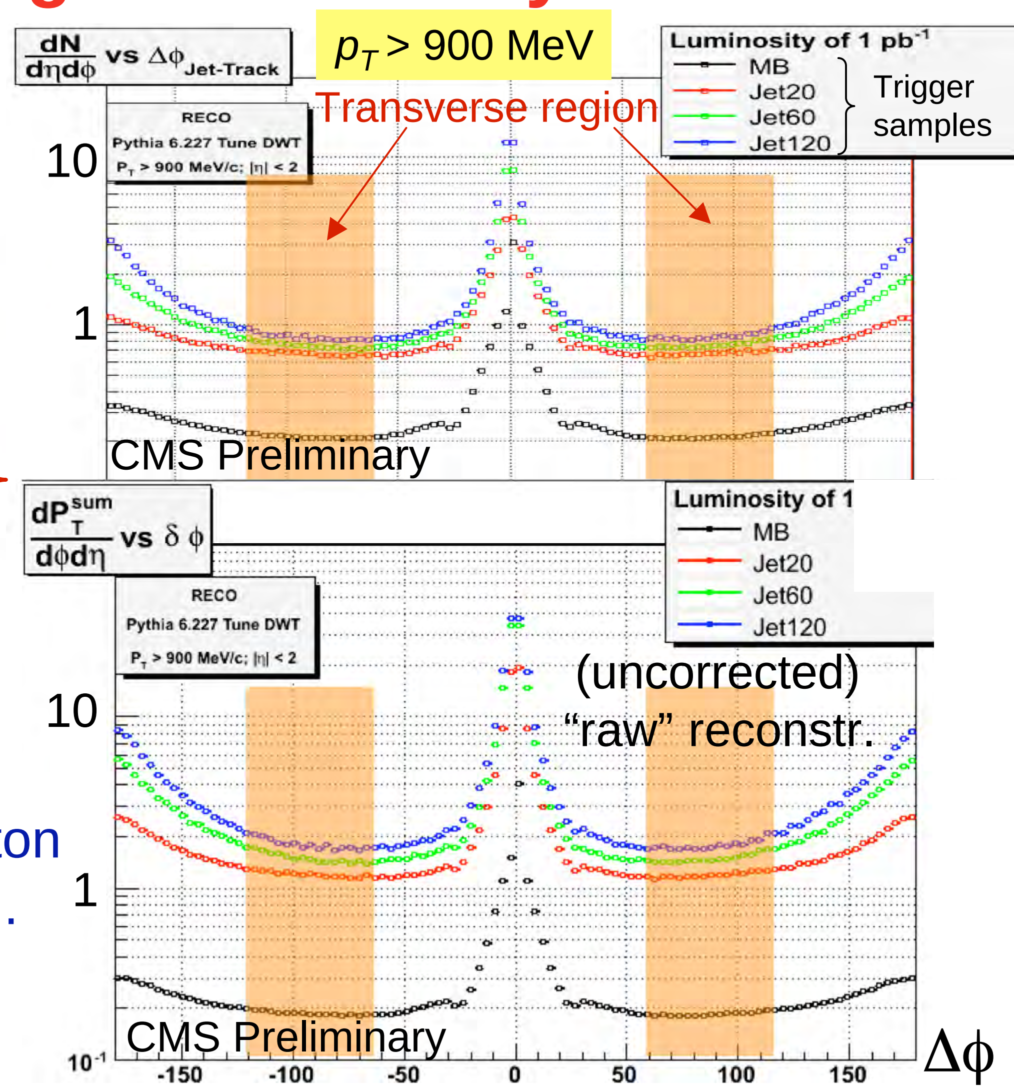
Event Structure: Underlying Event

Measuring the underlying event activity

- Observe $d^2N/d\eta d\phi$ and $d^2p_T^{sum}/d\eta d\phi$



Look in region ⊥ to jet activity: transverse region

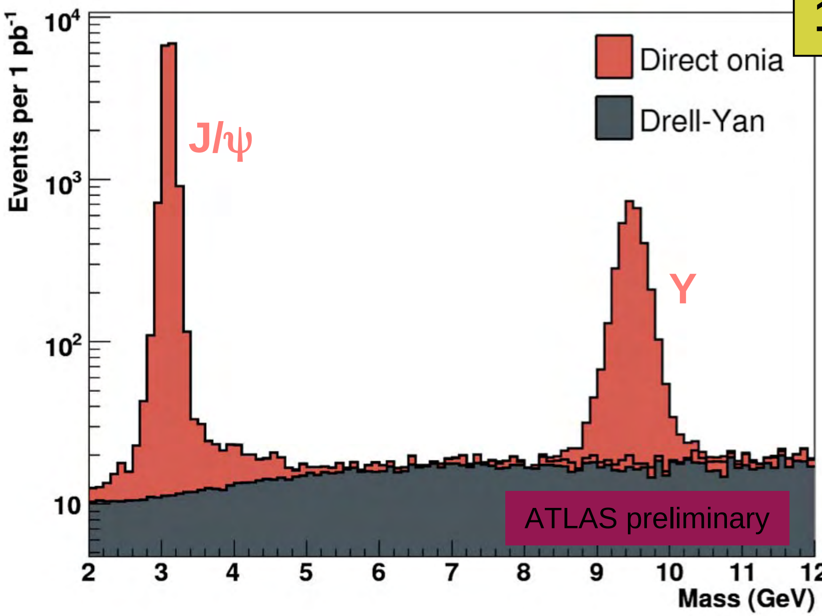


→ Important ingredient for jet & lepton isolation, energy flow, jet-tagging, …

→ sensitive to test multiple-parton interaction (MPI) tunes of QCD …

Standard Model Peaks

1 pb^{-1}≡3 days at 10^{31} at 30% efficiency

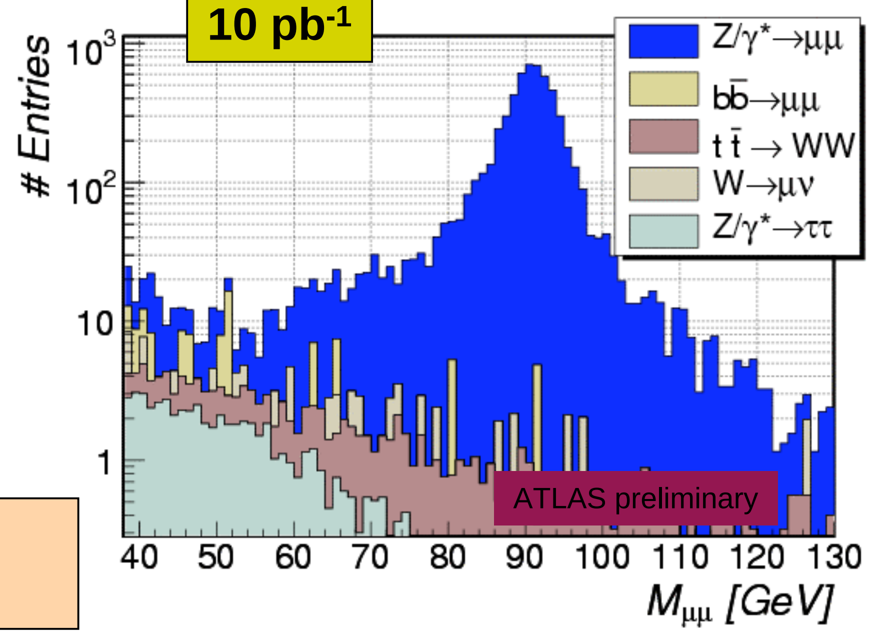


After all cuts:
~ 4200 (800) J/ψ (Y) → μμ evts per day at L = 10^{31}
(for 30% machine x detector data taking efficiency)
~ 15600 (3100) events per pb^{-1}

→ tracker momentum scale, trigger performance, detector efficiency, sanity checks, …

After all cuts:
~ 160 Z → μμ evts per day at L = 10^{31}
~ 600 events per pb^{-1}

10 pb^{-1}



→ Muon Spectrometer alignment, ECAL uniformity, energy/momentum scale of full detector, lepton trigger and reconstruction efficiency, …

Precision on σ (Z→μμ) with 100 pb^{-1}: <2% (experimental error), ~10% (luminosity)

W,Z cross sections w/10 pb^{-1}

Sufficient Statistics

- Cross section uncertainty dominated by luminosity measurement (10%)

Use data-driven methods to analyze W,Z obervables

Electron Channels:

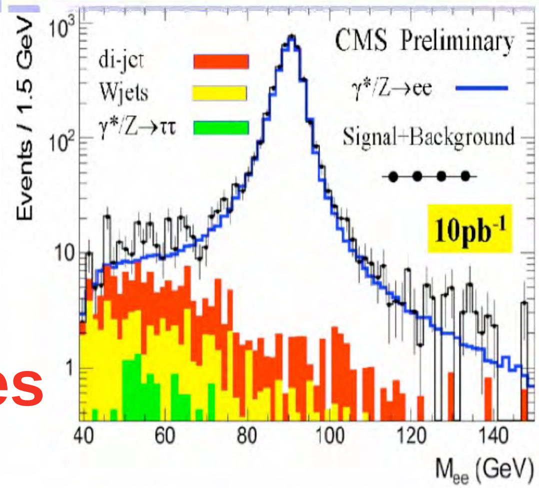
- Robust electron selection wrt. mis-calibration/alignment
- QCD Bkgd. significant for W

Muon Channels:

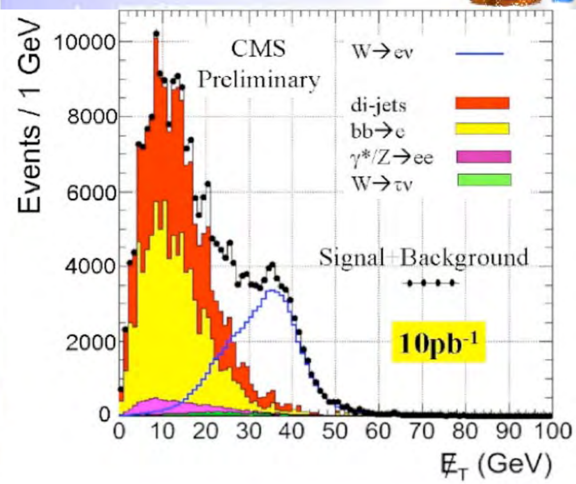
- Very clean
- Largest measurement syst. is momentum scale err. < 2.7%

Useful for PDFs

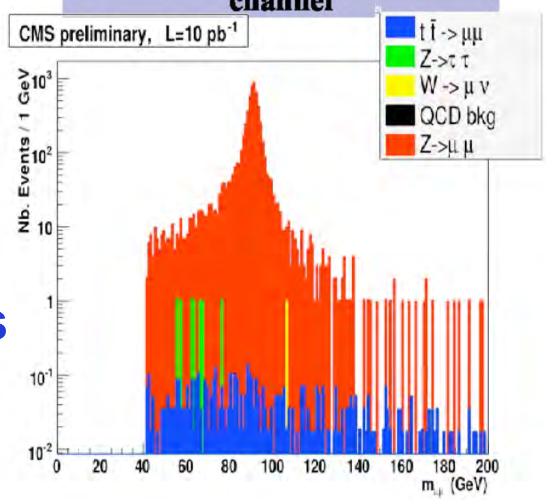
- w/100pb^{-1}…see later slides



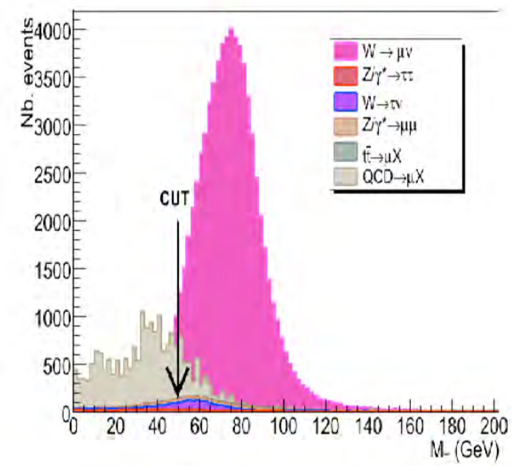
Z mass distribution using Z→ee channel



Missing Et distribution using W→eν channel



Z mass distribution using Z→μμ channel



M_T distribution using W→μν channel

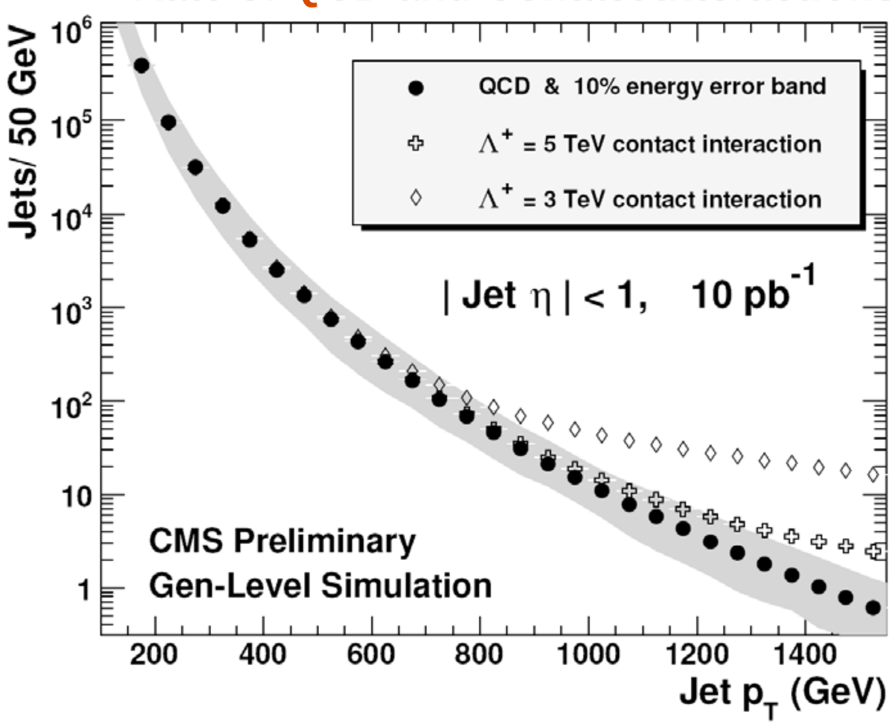
$10\ pb^{-1}$: Inclusive Jet p_T & Contact Interactions

Contact Interactions create large rate at high p_T and immediate discovery possible

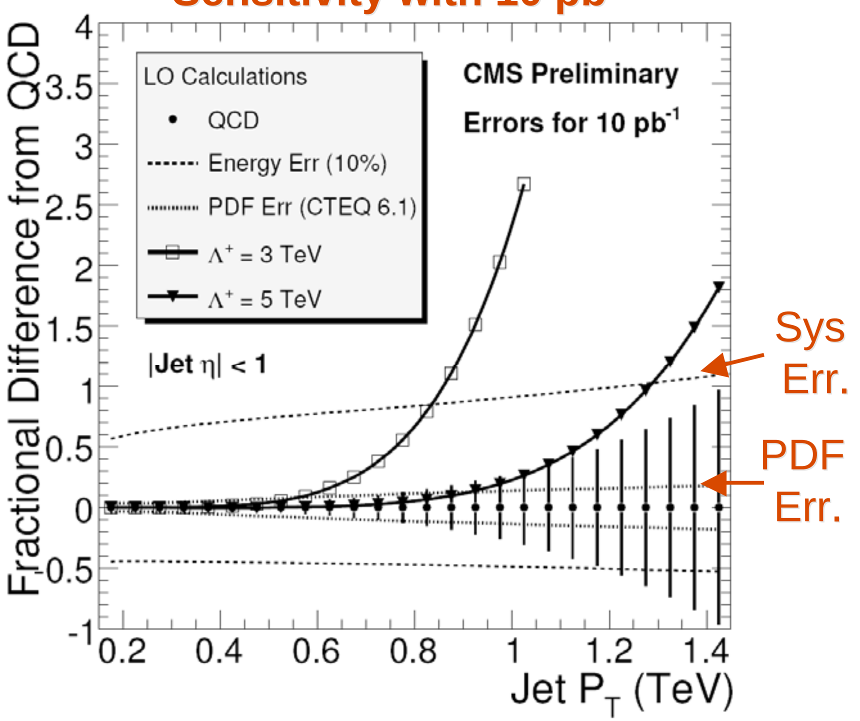
- Error dominated by Jet Energy Scale (~10%) in early running ($10\ pb^{-1}$)
  - DE~ 10% not as big an effect as L+= 3 TeV for pT>1 TeV
- PDF "errors" and statistical errors ($10\ pb^{-1}$) smaller than E scale error

With $10\ pb^{-1}$ see new physics beyond Tevatron exclusion of L+ < 2.7 TeV

Rate of QCD and Contact Interactions



Sensitivity with $10\ pb^{-1}$

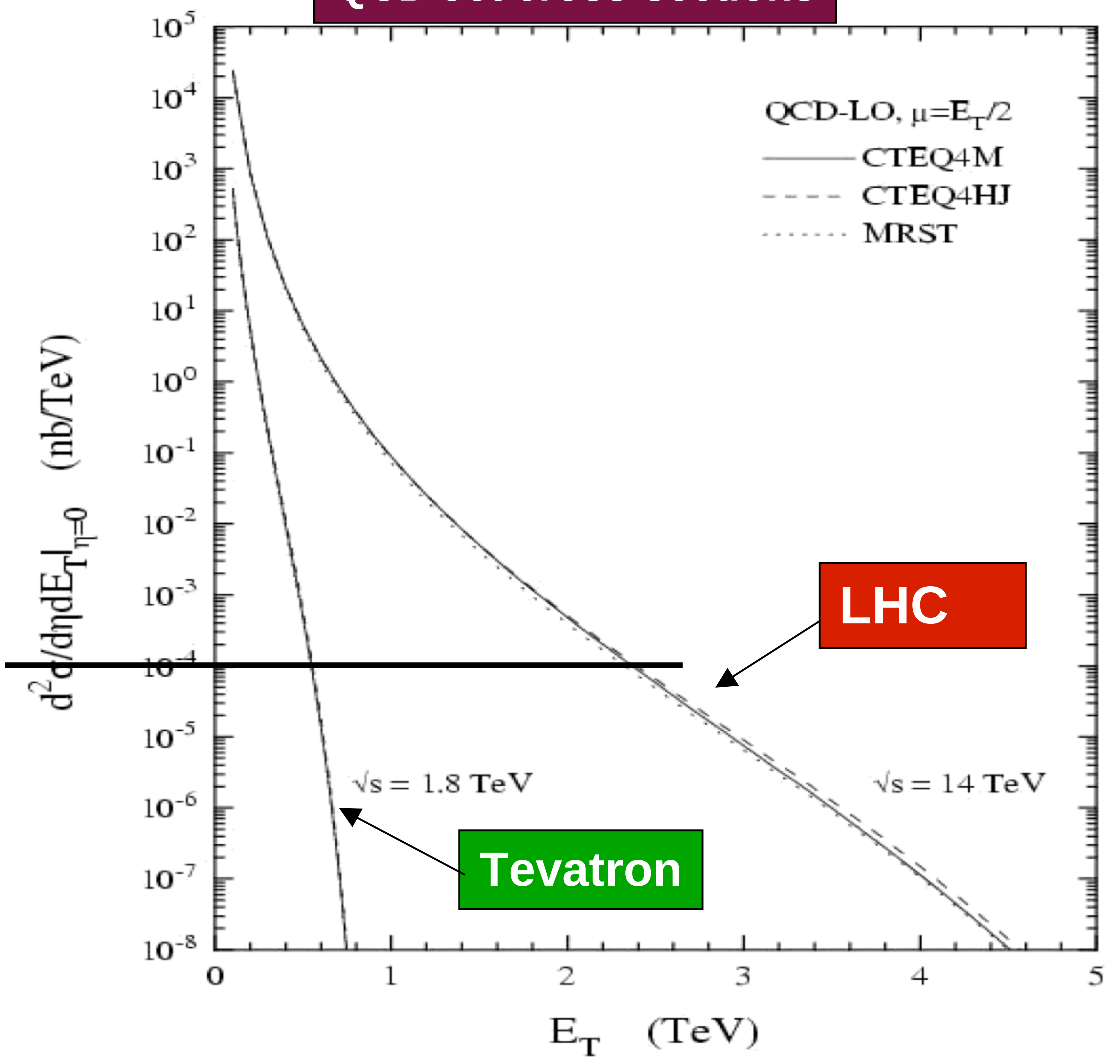


What about 100 pb^{-1}?

QCD Jet cross-sections

New Territory!

10 events with 100 pb^{-1}



What do you get per 100 pb^{-1}?

Channels (examples …)	Events to tape for 100 pb^{-1} (ATLAS)	Total statistics from LEP and Tevatron
$W \rightarrow \mu \nu$	~ 10^6	~ 10^4 LEP, ~ 10^{6-7} Tevatron
$Z \rightarrow \mu \mu$	~ 10^5	~ 10^6 LEP, ~ 10^{5-6} Tevatron
$tt \rightarrow W b W b \rightarrow \mu \nu + X$	~ 10^4	~ 10^{3-4} Tevatron
$\tilde{g}\tilde{g}$D jets $p_T > 1$ TeV	> 10^3	---
m = 1 TeV	~ 50	--

What do you do with it?

- **Commission and calibrate the detector in situ using well-known physics samples (time-consuming but essential)**
  - $Z \rightarrow ee, \mu\mu$: tracker, ECAL, Muon chamber calibration & alignment, etc.
  - $tt \rightarrow bl\nu\ bjj$: jet scale from $W \rightarrow jj$, b-tag performance, etc.
- **"Rediscover" and measure SM physics at $\sqrt{s}$ = 10, 14 TeV: W, Z, tt, QCD jets … (also time consuming & essential)**
  - also because omnipresent backgrounds to New Physics
- **Early discoveries?**
  - Potentially accessible: Z', SUSY, Higgs?, something else??

Dijet Resonances in Rate vs Dijet Mass

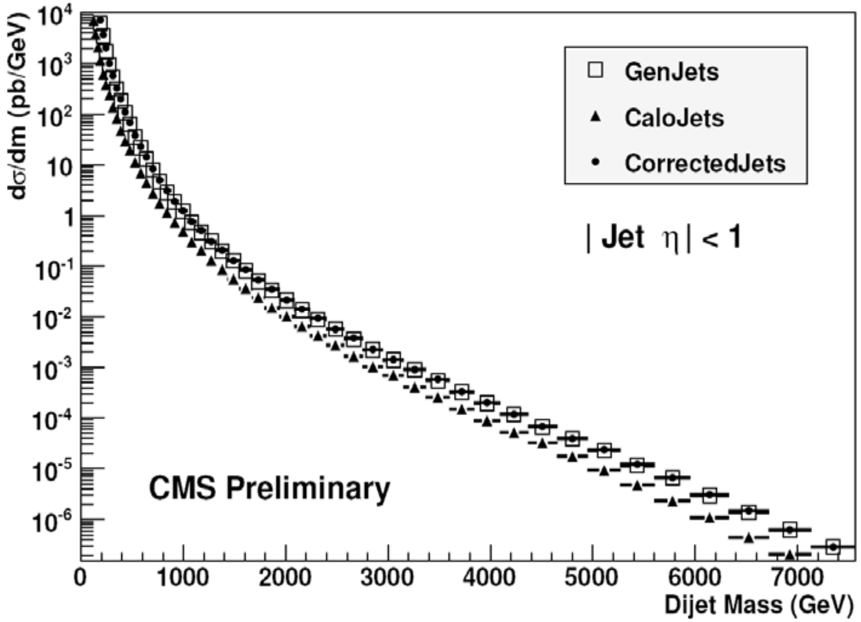
Measure rate vs Corrected Dijet Mass & look for resonances

- Use smooth parameterized fit or QCD prediction to model background

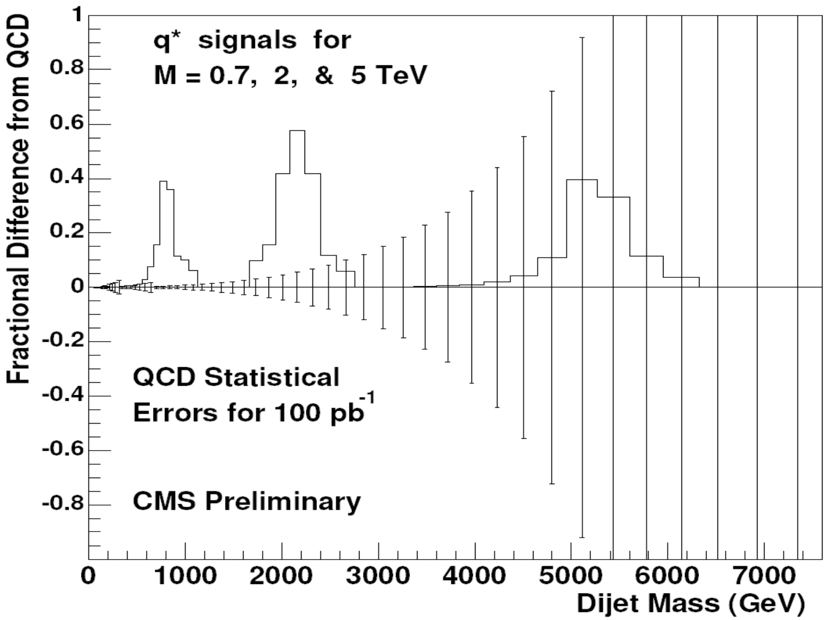
Strongly produced resonances can be seen

- Convincing signal for a 2 TeV excited quark in 100 pb^{-1}

QCD Backgound



Resonances with 100 pb^{-1}



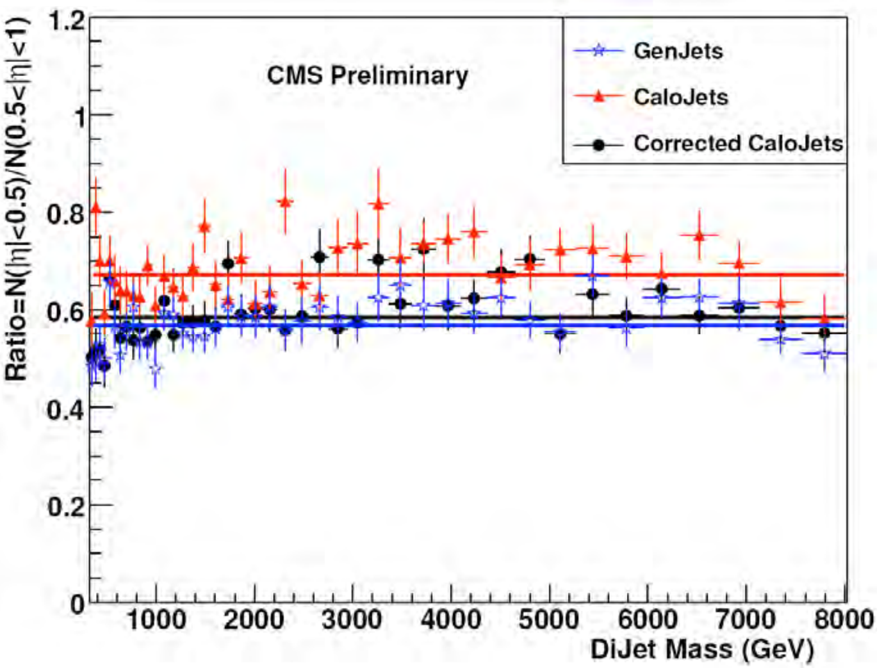
Dijet Ratio from QCD & Contact Interactions

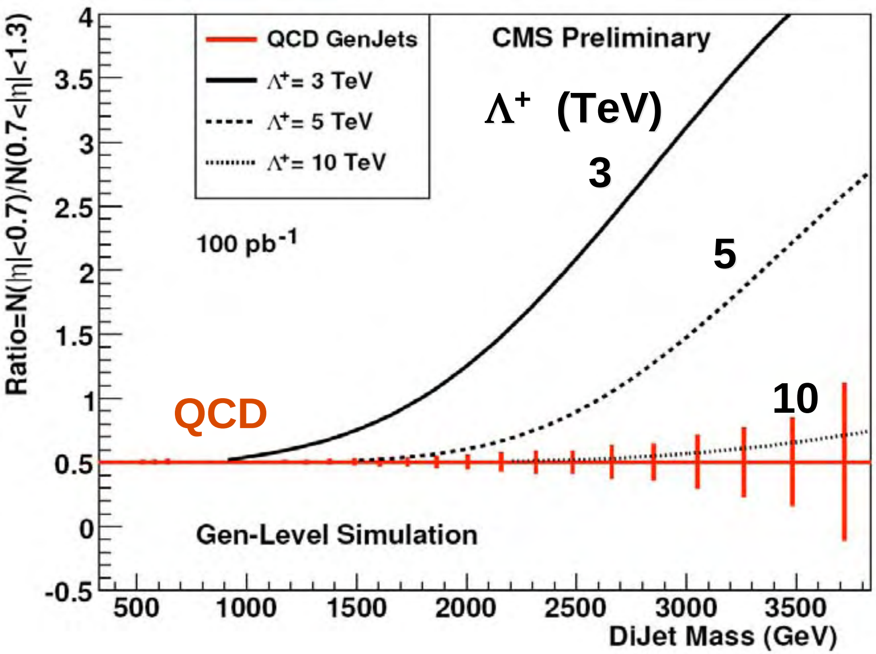
Optimize the dijet ratio for a Contact Interaction search in CMS barrel

- QCD cross section rises dramatically with |η| cut due to t-channel pole
- Z' signal only gradually increases with |η| cut ⇒ optimal value at low |η|
- Optimal: |η| < 1.3 for 2 TeV dijet resonance: Dijet Ratio is N(|η|<0.7) / N(0.7<|η|<1.3)

Increases sensitivity to contact interactions over previous CMS value

- Raising the signal and decreasing the QCD error bars
- Value of Λ^+ discoverable increased by 2 TeV for 100 pb^{-1} over CMS Physics TDR
  - From $\Lambda^+ \approx$ 5 TeV with old dijet ratio (PTDR) to $\Lambda^+ \approx$ 7 TeV with new dijet ratio

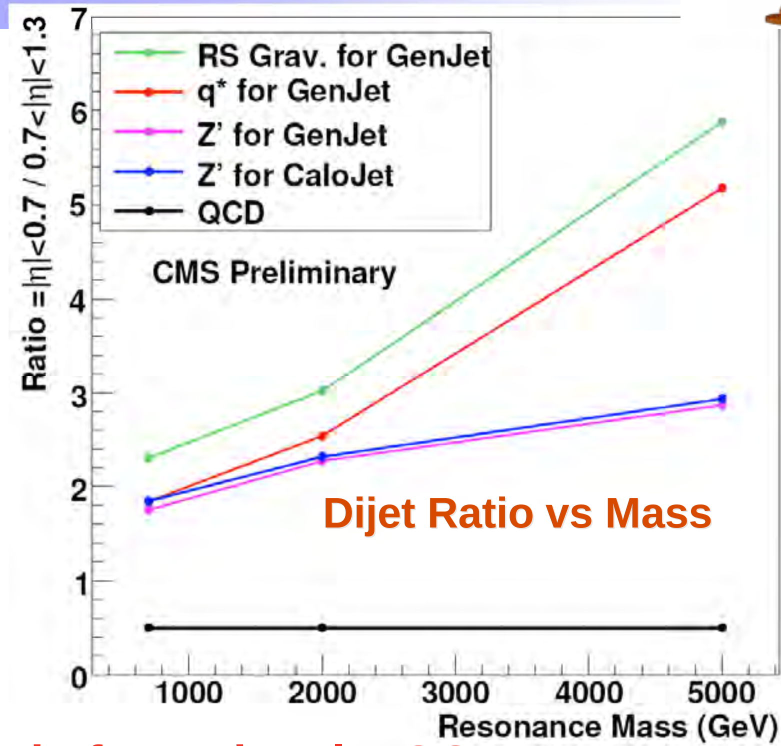




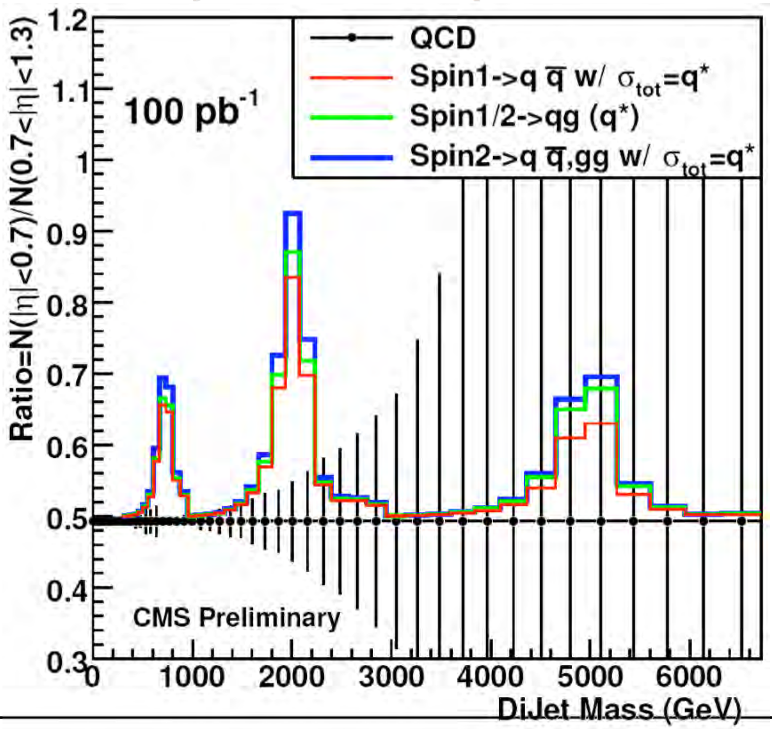
Dijet Resonances & Dijet Ratio

Spin 1/2 (q*), spin 1 (Z'), and spin 2 (RS Graviton) resonances are more isotropic than QCD in dN/dcosθ*

Resonances Dijet Ratio larger than for QCD because numerator mainly low cosθ* and denominator mainly high cosθ*



Dijet Ratio for Spin 1/2, 1, 2



Dijet Ratio from signal + QCD compared to statistical errors for QCD

- Resonances normalized with q* cross section for |η|<1.3 to see effect of spin

Convincing signal for 2 TeV strong resonance in 100 pb^{-1} regardless of spin

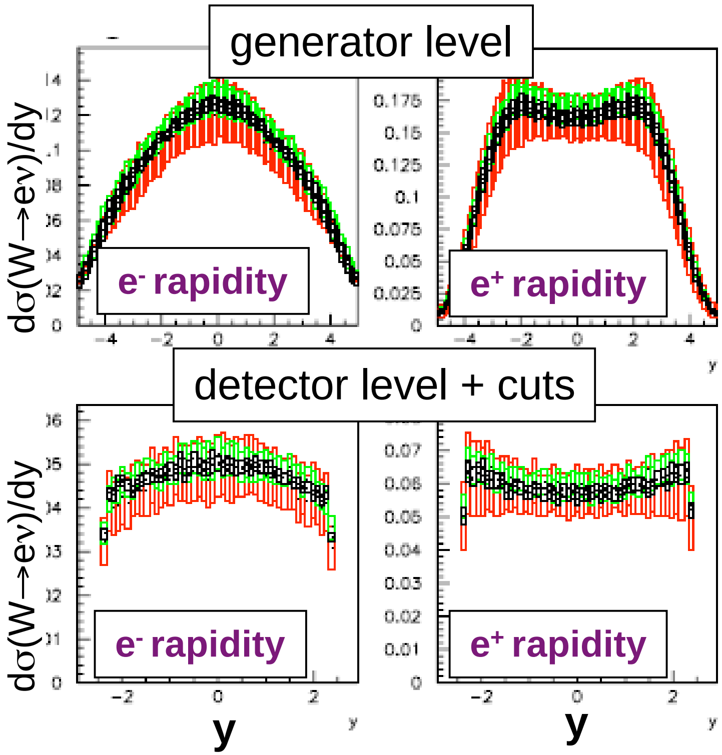
Technique for discovery, confirmation and eventually spin measurement

LHC Data & PDFs

Constraining PDF with early data using W → lν angular distributions

$$x_{1,2} = \frac{M}{\sqrt{s}} \exp(\pm y)$$

⇒ W production over |y|<2.5 at LHC involves $10^{-4} < x_{1,2} < 0.1$
⇒ region dominated by g → qq

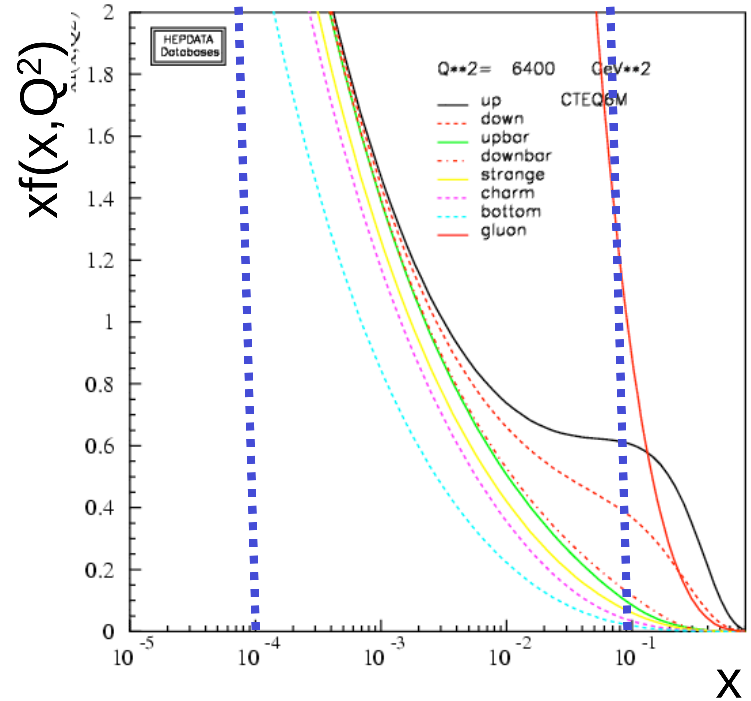


HERWIG + NLO K-factor

CTEQ61

MRST01

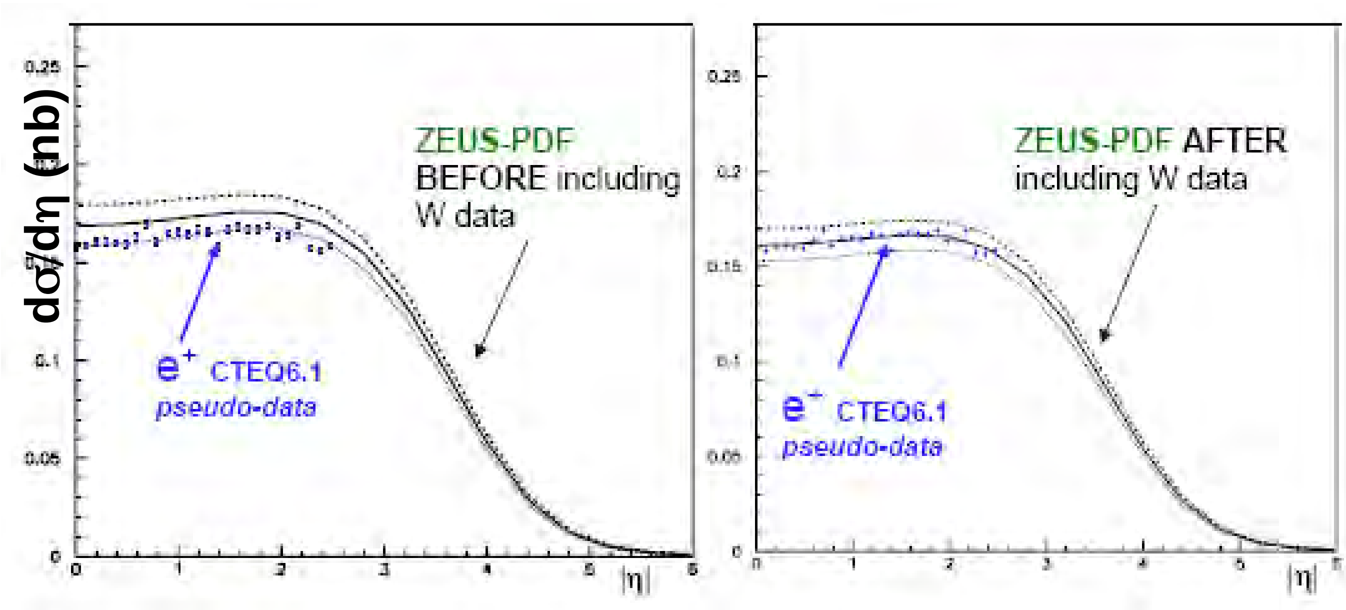
ZEUS-S



Uncertainties on present PDF: 4-8%
→ Early measurements of e± angular distributions at LHC can provide discrimination between different PDF if experimental precision is ~ 4%

Effect of LHC Data on PDFs

Sample of 10^6 W→ eν generated with CTEQ6.1 PDF and ATLAS fast simulation
Statistics corresponds to ~ 150 pb^{-1}
4% systematic error introduced by hand (statistical error negligible)
Then these pseudo-data included in the global ZEUS PDF fit



Absolute normalization left free in the fit (not to depend on knowledge of luminosity).
W^+/W^- relative normalization depends on PDF

Central value of ZEUS-PDF prediction shifts and uncertainty is reduced
Error on low-x gluon shape parameter λ [xg(x) ~ $x^{-\lambda}$] reduced from 23% to 15%

Systematics (e.g. $e^{\pm}$ acceptance vs η) controllable to few percent with Z → ee
(~ 30000 events for 100 pb^{-1})

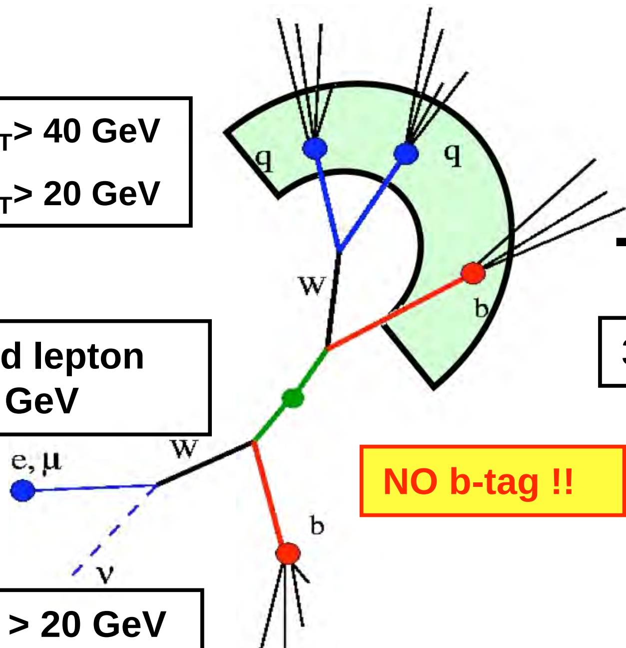
Observation of top signal

Tops are central & back-to-back → observed quickly, even w/limited detector performance
→ used to calibrate the detector and understand physics

3 jets p_T> 40 GeV
1 jets p_T> 20 GeV

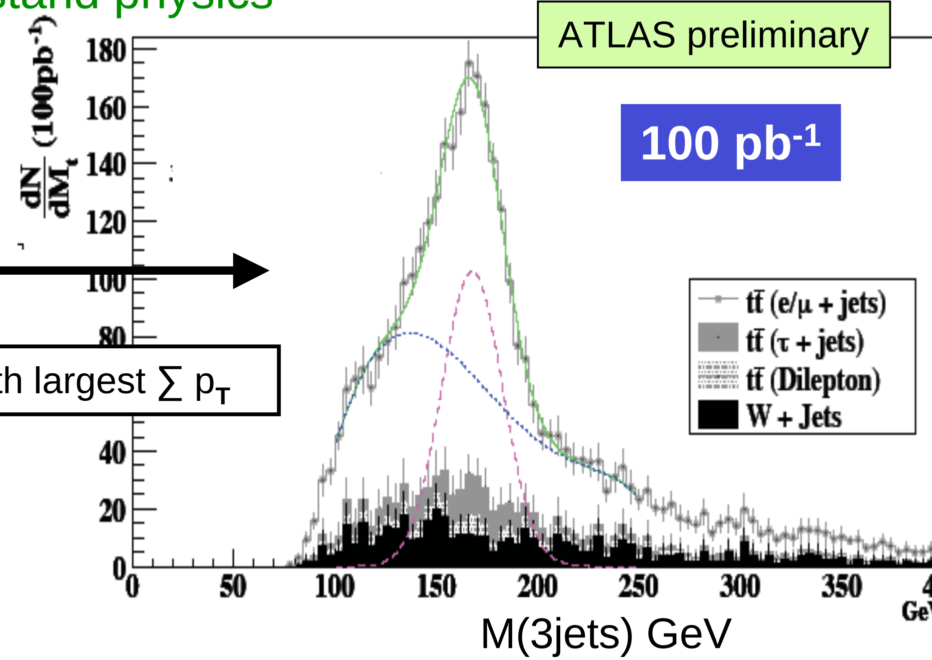
Isolated lepton
p_T> 20 GeV

E_T^{miss} > 20 GeV



NO b-tag !!

3 jets with largest $\sum p_T$



$\sigma_{tt} \approx$ 250 pb for tt → bW bW → blν bjj

Top signal observable in early days with no b-tagging & simple analysis
(~1000 evts for 30 pb^{-1}) → measure σ_{tt} to ~20%, m_t to <10 GeV with 100 pb^{-1}

In addition, excellent sample to:
- **commission b-tagging, set jet E-scale using W → jj peak, …**
- **understand / constrain theory and MC generators using e.g. p_T spectra**

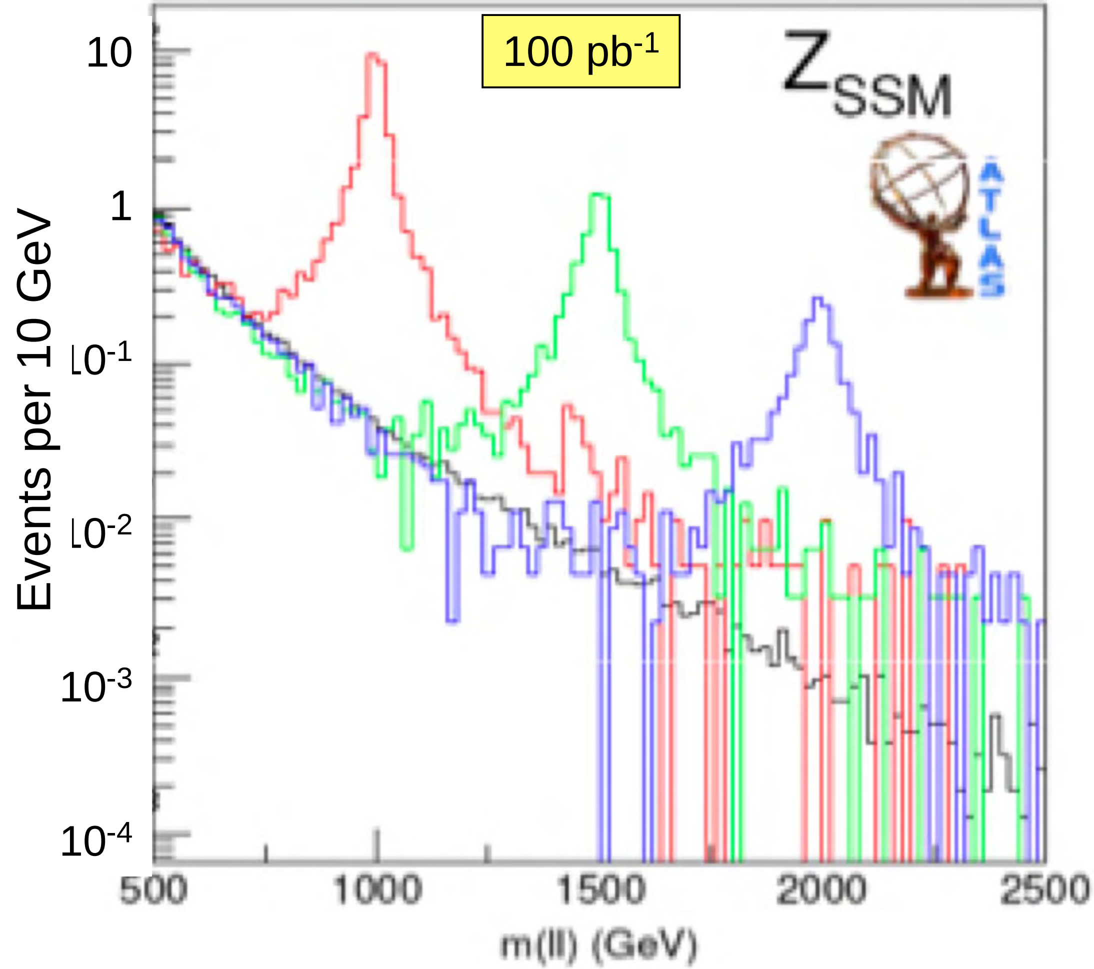
Resonances

A good candidate: a narrow resonance with mass ~ 1 TeV decaying into e^+e^- with 100 pb^{-1}

Large enough signal for discovery up to m > 1 TeV

Signal is (narrow) mass peak on top of small Drell Yan background

Ultimate calorimeter performance not needed

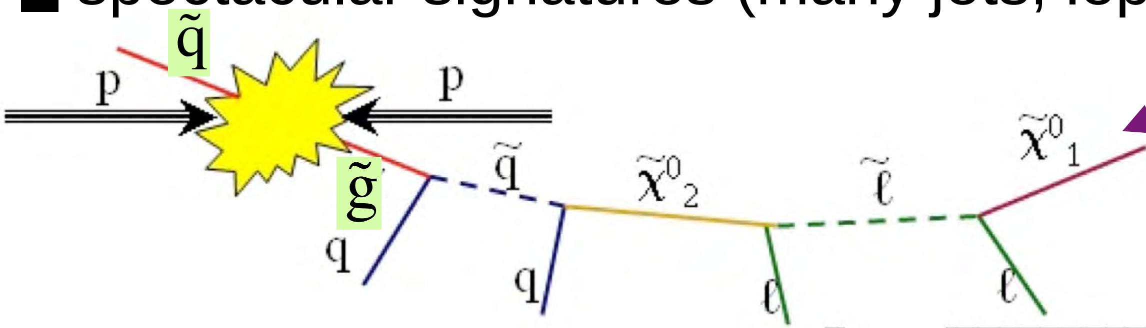


Is it a Z' or a Graviton ? From angular distribution of e^+e^- can disentangle Z' (spin=1) from G (spin=2). Requires more data (~ 100 fb^{-1})

Supersymmetry

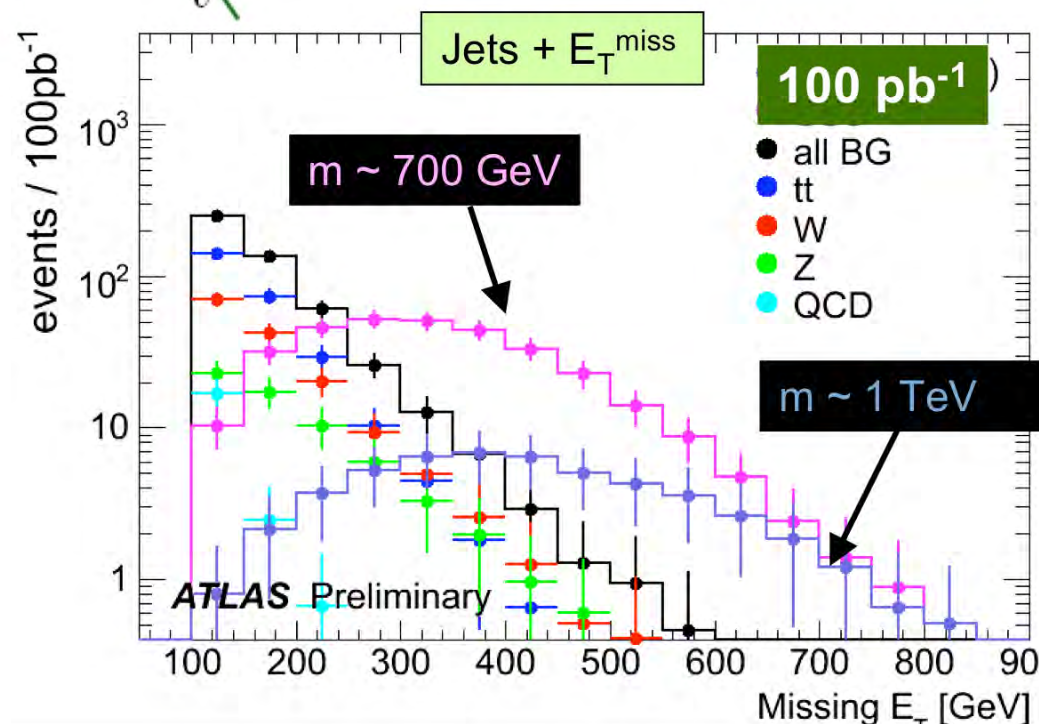
large (strong) cross-section for $\tilde{q}\tilde{q}, \tilde{g}\tilde{q}, \tilde{g}\tilde{g}$ production

- spectacular signatures (many jets, leptons, missing E_T)



For $m(\tilde{q},\tilde{g}) \sim 1$ TeV
expect 10 evts/day at $L=10^{32}$

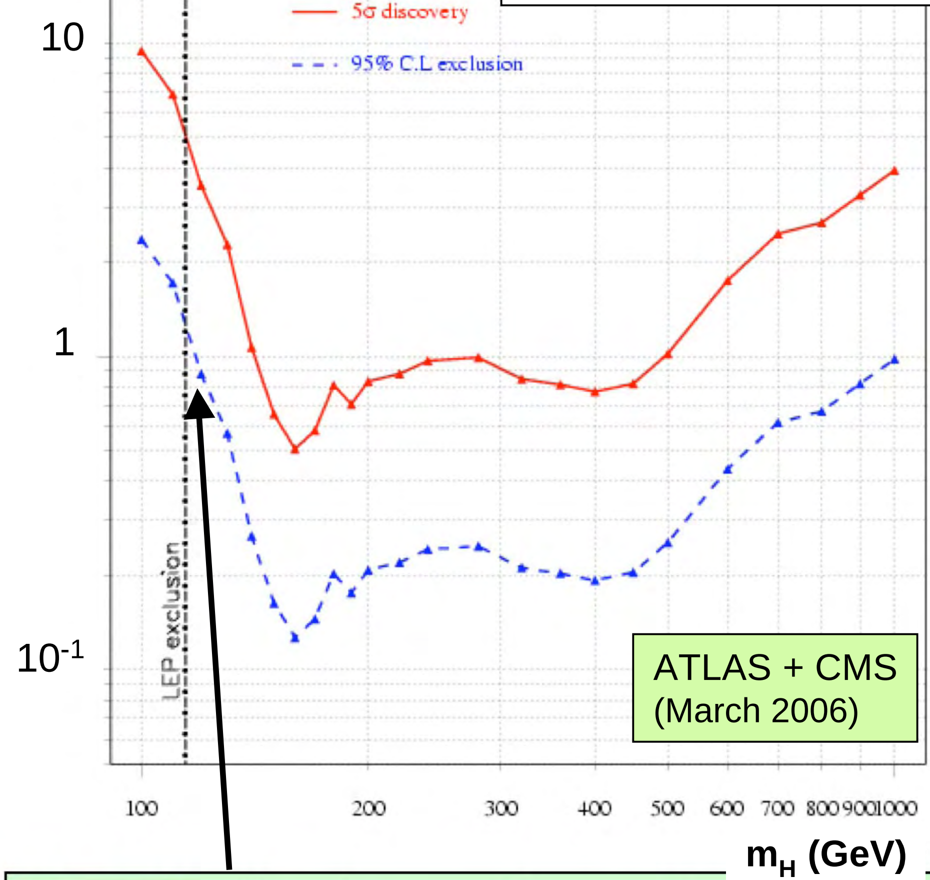
Hints with only 100 pb^{-1} up to m~1 TeV, but understanding backgrounds requires ~1 fb^{-1}



Post Startup: Higgs Boson

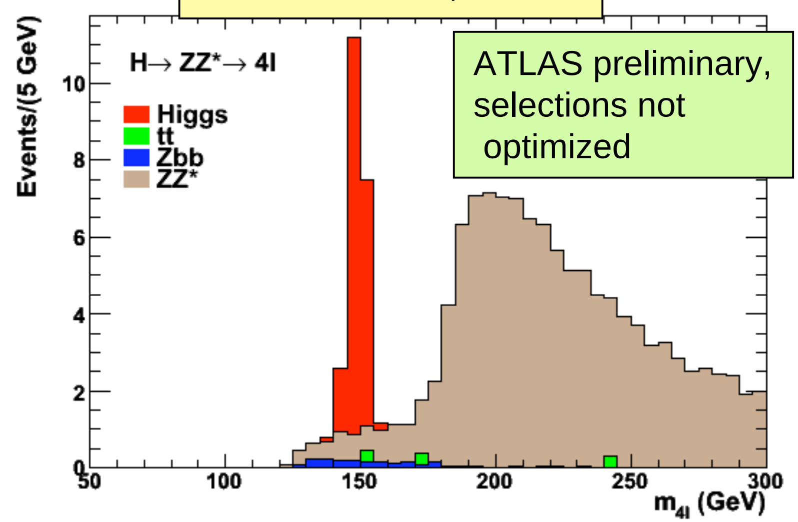
Needed ∫Ldt (fb^{-1})
of well-understood data
per experiment

$\leq$ 1 fb^{-1} for 95% C.L. exclusion
$\leq$ 5 fb^{-1} for 5σ discovery
over full allowed mass range



For m_H > 140 GeV discovery easier with $H \to ZZ^{(*)} \to 4l$ (narrow mass peak, small B).
$H \to WW \to l\nu l\nu$ (dominant at 160-175 GeV) is counting experiment (no mass peak)

$H \to ZZ^* \to 4l$, 10 fb^{-1}



Most difficult region: need to combine many channels (e.g. $H \to \gamma\gamma$, $qqH \to qq\tau\tau$) with small S/B

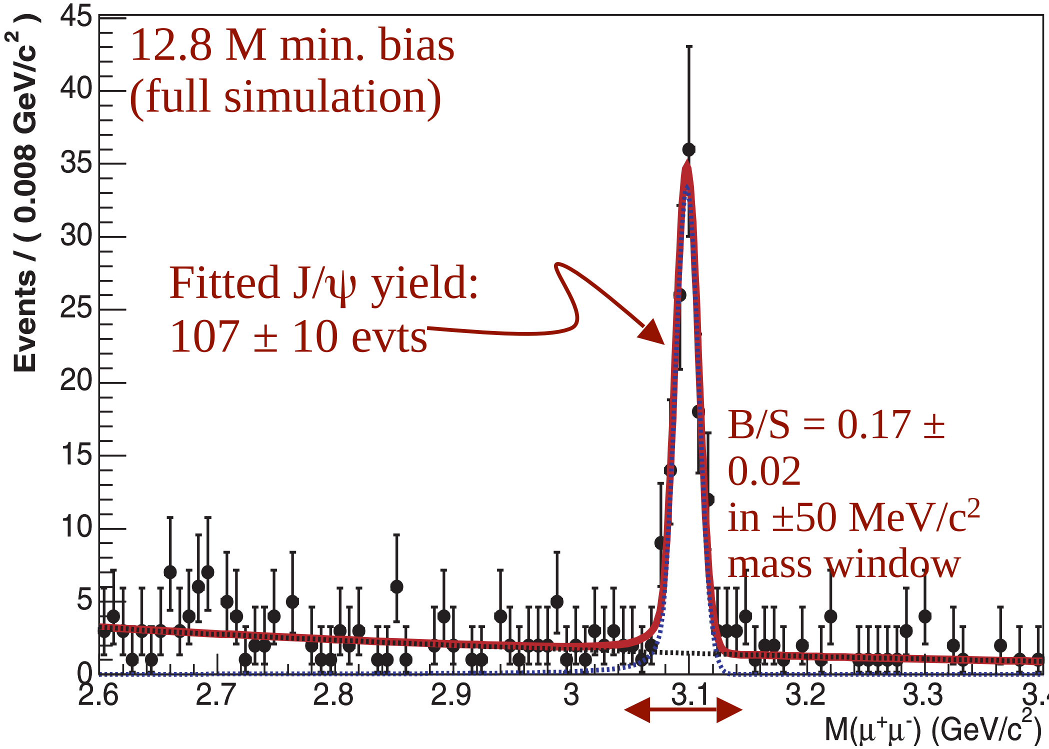
LHCb Physics with early data

Minimum bias events:

- e.g. 10^8 events in ~20 hours at 2×10^{28} $cm^{-2}s^{-1}$ with interaction trigger
- First look at 10 TeV & then 14 TeV data: everything new !
  - (Ratio of) multiplicities vs η, p_T, φ of charged tracks (+/–, π/K/p)
  - Reconstruction and production studies of K_S, Λ, ϕ, D, …

$J/\psi \rightarrow \mu\mu$ events:

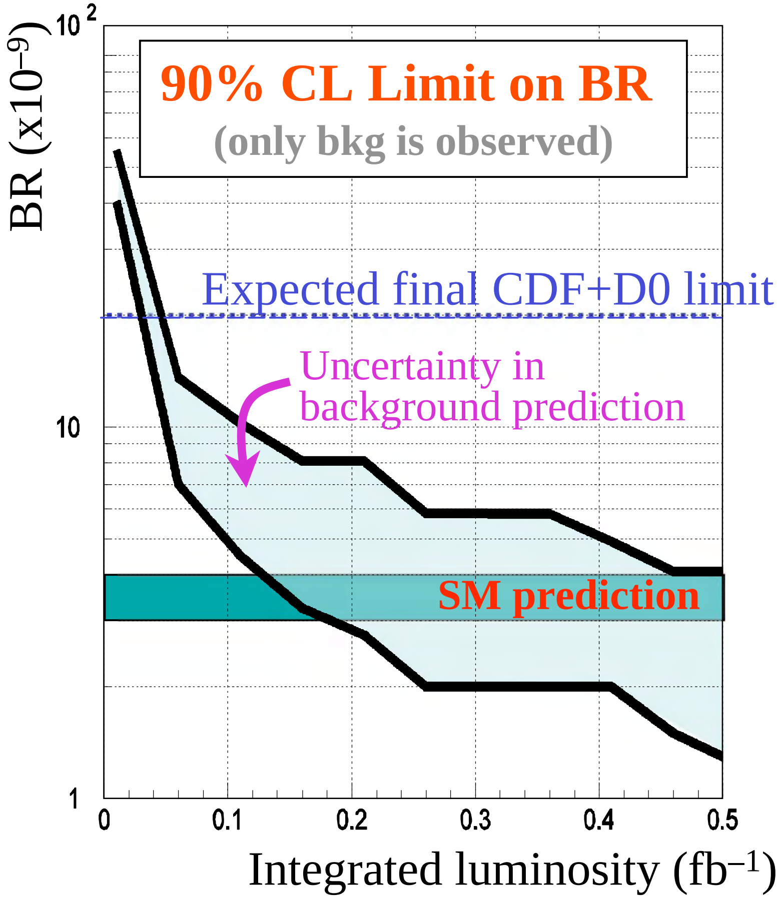
- ~1M $J/\psi \rightarrow \mu\mu$ in 1 pb^{-1} (little bit of trigger needed)
  - Fraction of J/ψ from b decays or prompt production vs p_T
  - First exclusive $B \rightarrow J/\psi X$ peaks
  - Measurements of bb production cross section, …



LHCb: $B_s \rightarrow \mu^+\mu^-$

"Easy" for LHCb to trigger and select

- **Large total efficiency (10%)**
- **Main issue is background rejection**
  - study based on limited MC statistics
  - largest background is b→μ, b→μ
  - specific background dominated by $B_c \rightarrow J/\psi(\mu\mu)\mu\nu$
- **Exploit good detector performance:**
  - muon ID
  - vertexing (topology)
  - mass resolution (18 MeV/c^2)



0.05 fb^{-1} ⇒ overtake CDF+D0
0.5 fb^{-1} ⇒ exclude BR values down to SM
2 fb^{-1} ⇒ 3σ evidence of SM signal
6 fb^{-1} ⇒ 5σ observation of SM signal

LHCb's best NP discovery potential with the very early data !

Early ALICE pp Data

First physics in ALICE will be pp

- provides important “reference” data for heavy ion program

Particle ID→ tune MinBias MC, Jet Frag.

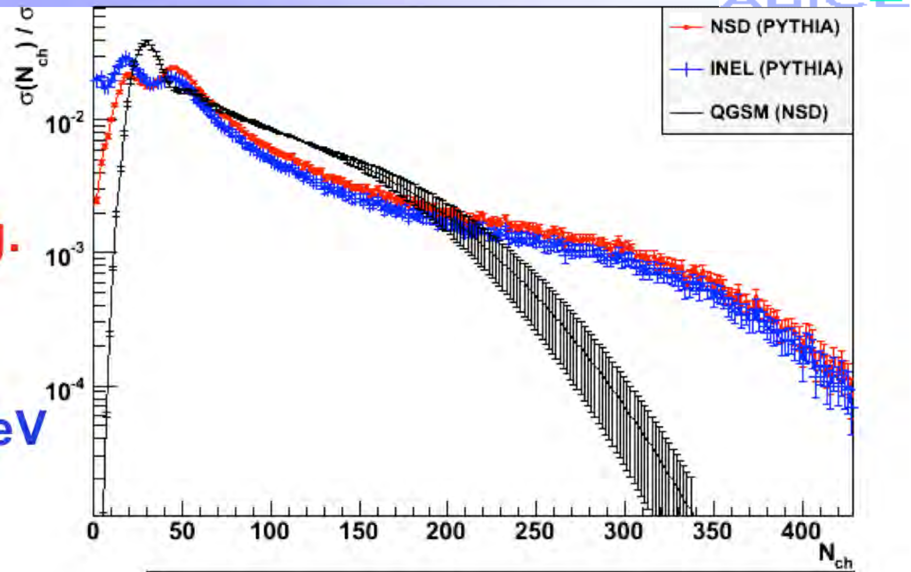
- $\pi^{\pm}$, K, p: 100 MeV < p < 50 GeV
- e: TRD: p > 1 GeV, μ: p > 5 GeV
- weak decays & resonances 0.5 to >10 GeV
- π^0 in PHOS: 1 < p < 80 GeV

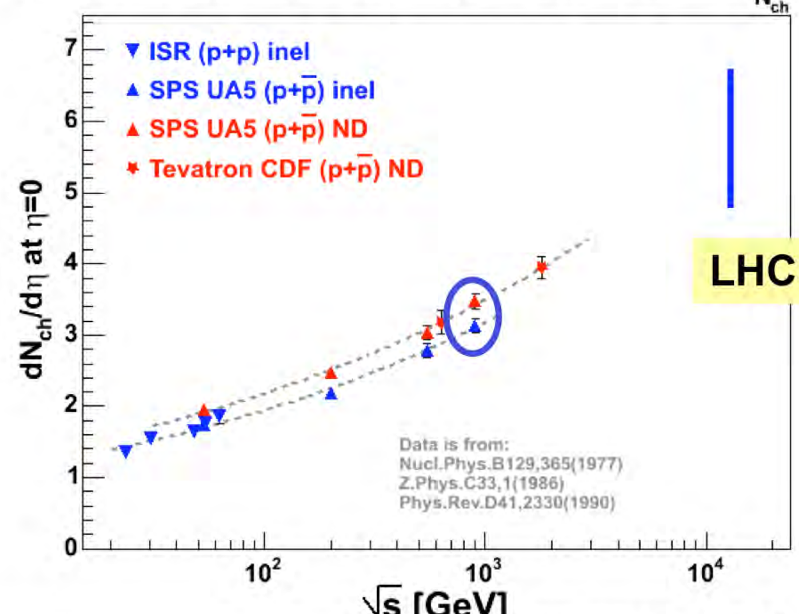
Unique pp physics in ALICE e.g.

- multiplicity distribution (shown here)
- baryon transport
- measurement of charm cross section major input to pp QCD physics

Charged Particle Multiplicity

- extend existing energy dependence
- unique SPD trigger (L0) for min. bias precision measurement
- completely new look at fluctuations in pp (neg. binomials, KNO…)





Baryon-AntiBaryon Assym.

Distinguish baryon number transport models

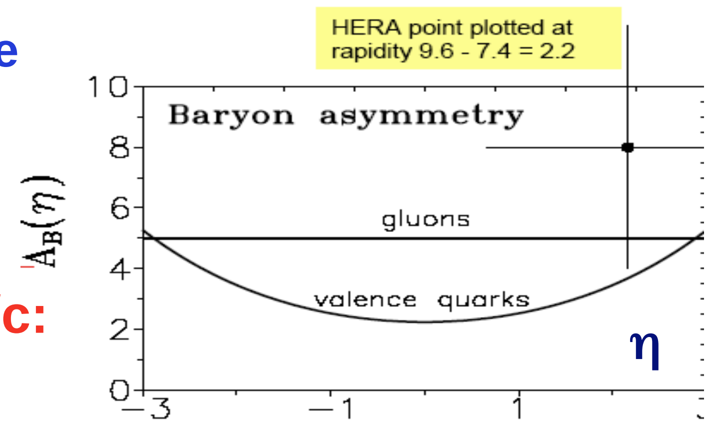
- via quark exchange vs. string junction exchange

Large rapidity gap at LHC (> 9 units)

- predicted absolute value of 2nd case ~ 3-7%
- also predict: asymmetry multiplicity dependent

Assym. systematic error < 1% for p > 0.5 GeV/c:

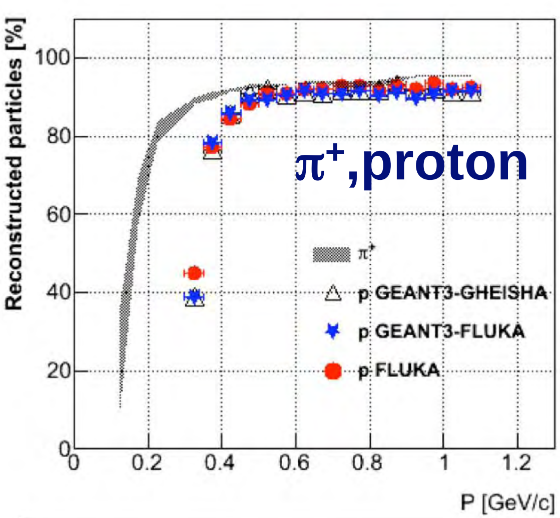
- contributions from uncertainties in the cross sections, material budget, beam gas events

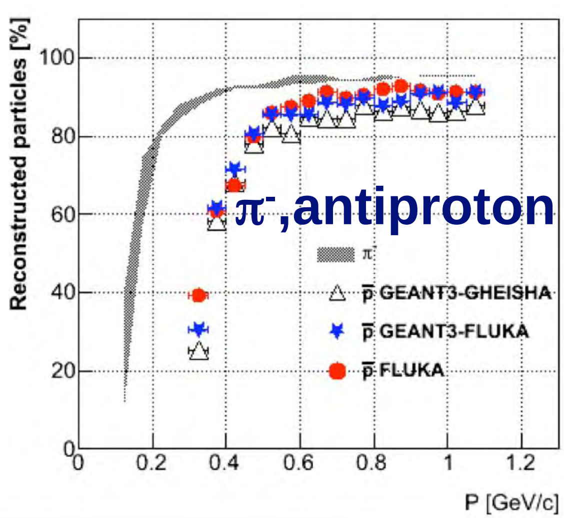


Phys. Lett. B446 (1999) 321: H1 data

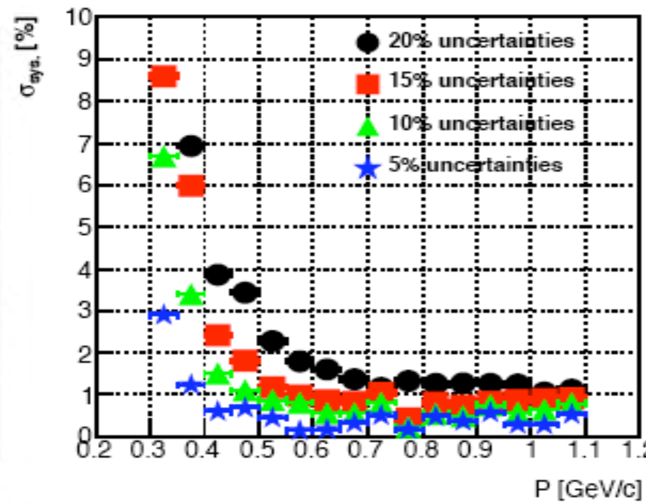
Statistical error < 1% for 10^6 pp events (< 1 day)

Can be extended to Λ,Λ (asymmetry larger)





ALICE Measurement: ASYMMETRY



Final Thoughts

The LHC is starting up -- are you ready?

If you are a theorist, are you ready to understand the first data results?

If you are an LHC experimentalist, are you ready to analyze the first data?

If you are a particle physics experimentalist not working on the LHC, are you ready to look in your own data for signs of what the first glimpse of LHC data tell us?

"Fain would I climb, yet fear I to fall" -- Sir Walter Raleigh
"If thy heart fail thee, climb not at all." -- Queen Elizabeth I