Total, elastic & diffractive cross-sections

K. Österberg,
Department of Physics, University of Helsinki
& Helsinki Institute of Physics

INFN LS1 Elba 23.5.2014

- elastic scattering
- total cross-section

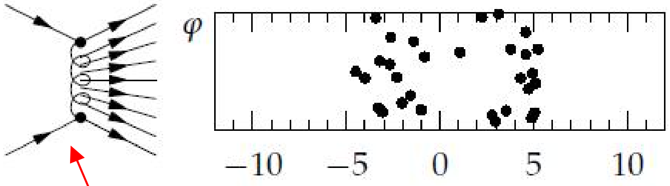
$\left.\right\}$ TOTEM (& ATLAS ALFA)

- diffraction: HERA, Tevatron, ALICE, CMS (&) TOTEM
- central exclusive production: CDF, D0, LHCb, ALICE, CMS(&TOTEM)...in future CMS-TOTEM PPS, ATLAS AFP, LHCb Herschel

O(100 mb) $\leftrightarrow$ O(fb)
NPQCD & QED $\leftrightarrow$ search for BSM physics

Classification of soft pp events

Non-Diffractive process (ND) ≈ 60 mb @ $\sqrt{s}$ = 7 – 8 TeV



Non-diffractive

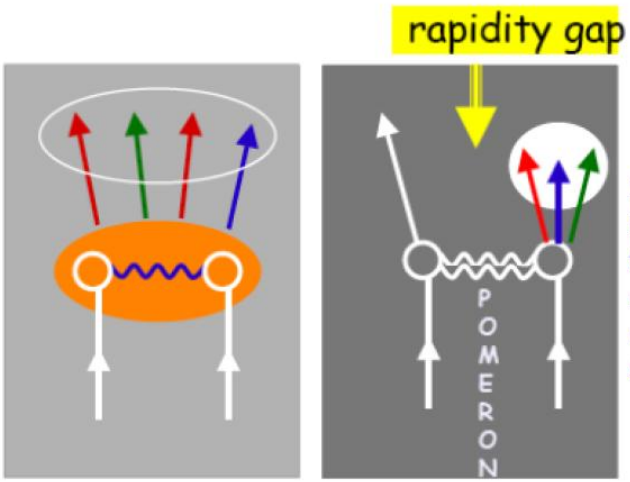
Colour exchange

$dN / d\Delta\eta = \exp(-\Delta\eta)$

Diffractive

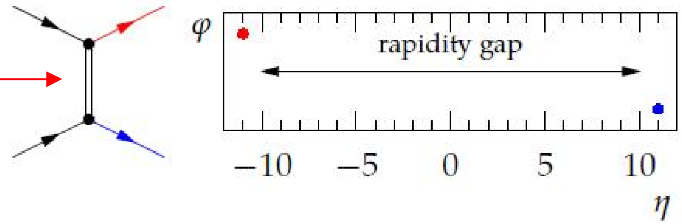
Colourless exchange with vacuum quantum numbers

$dN / d\Delta\eta = \text{const}$

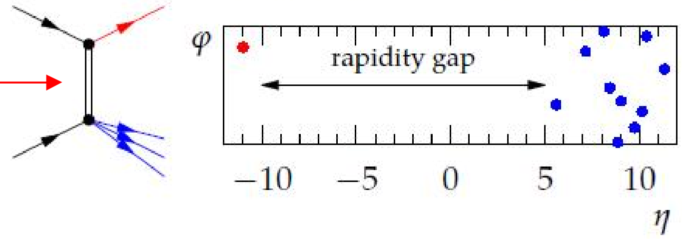


Incident hadrons retain their quantum numbers remaining colourless

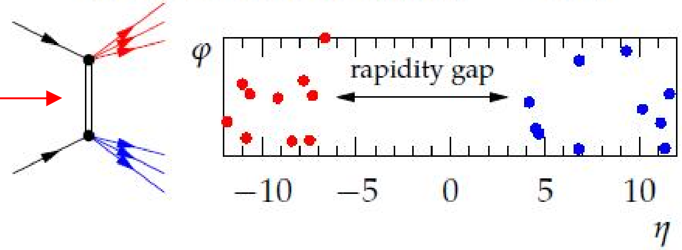
Elastic Scattering (ES), ≈ 25 mb



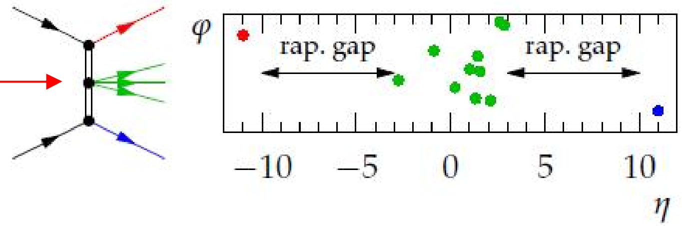
Single Diffraction (SD), ≈ 10 mb



Double Diffraction (DD), ≈ 5 mb



Central Diffraction (CD), ≈ 1 mb



- Experimental signiture: leading protons and/or rapidity gaps
- QCD picture: pure combination of color-compensated gluons e.g. gluon pair/ladder

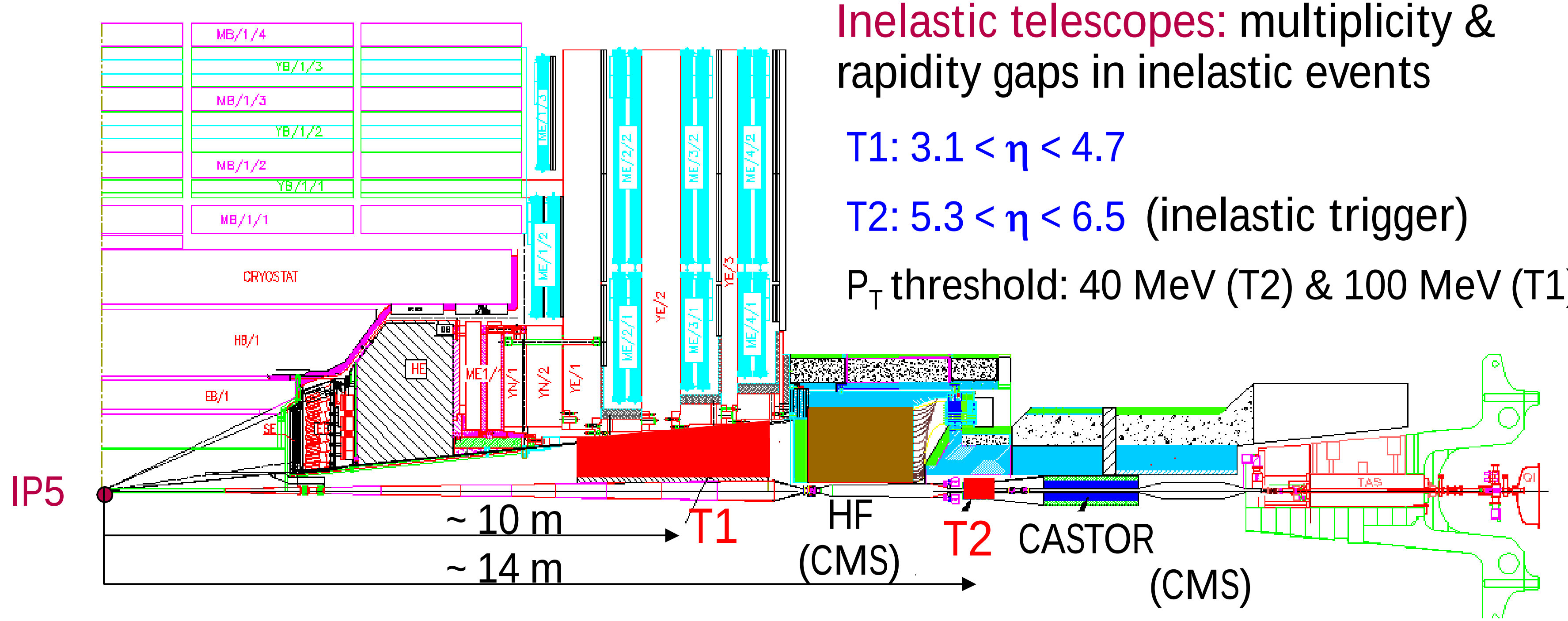
TOTEM experimental setup @ IP5

Inelastic telescopes: multiplicity & rapidity gaps in inelastic events

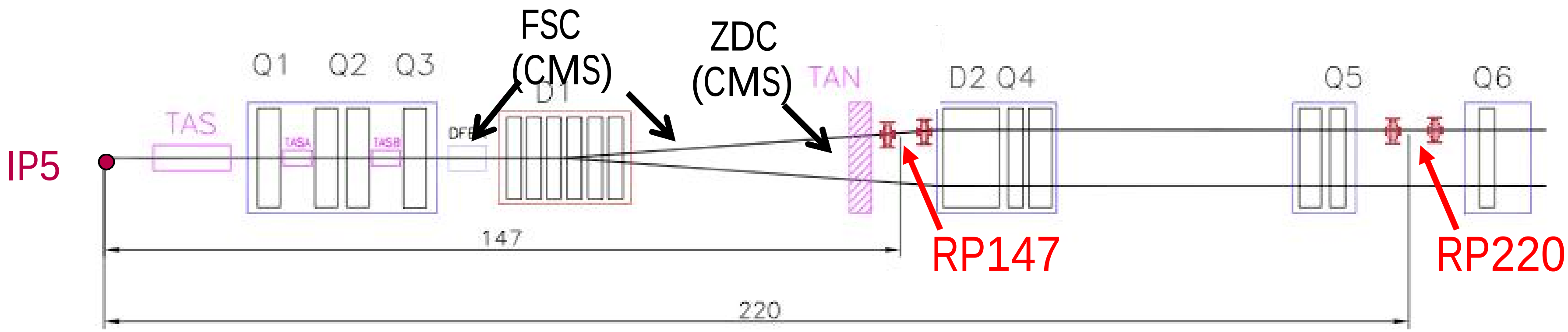
T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$ (inelastic trigger)

P_T threshold: 40 MeV (T2) & 100 MeV (T1)

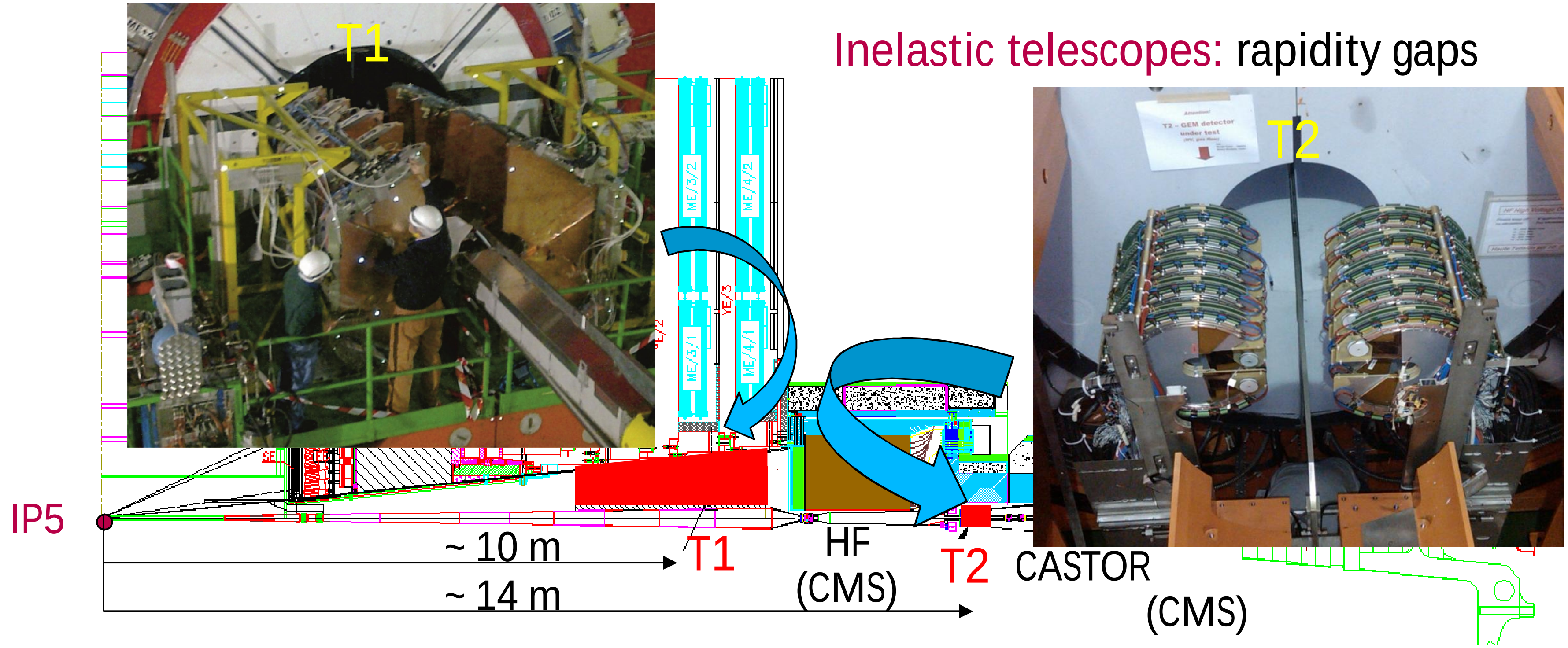


Roman Pots: elastic & diffractive protons (di-proton trigger)

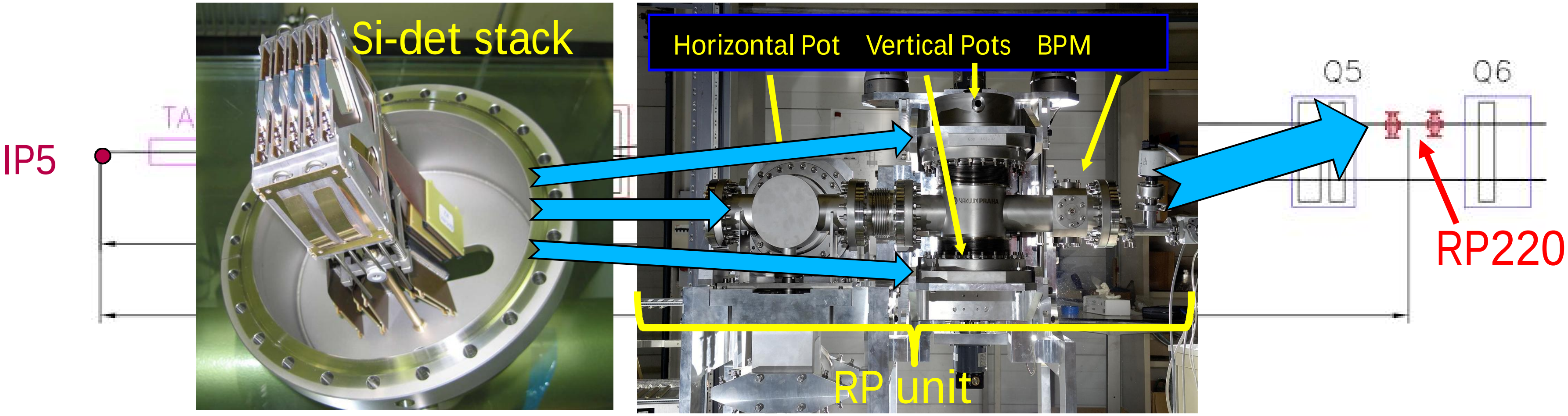


TOTEM experimental setup @ IP5

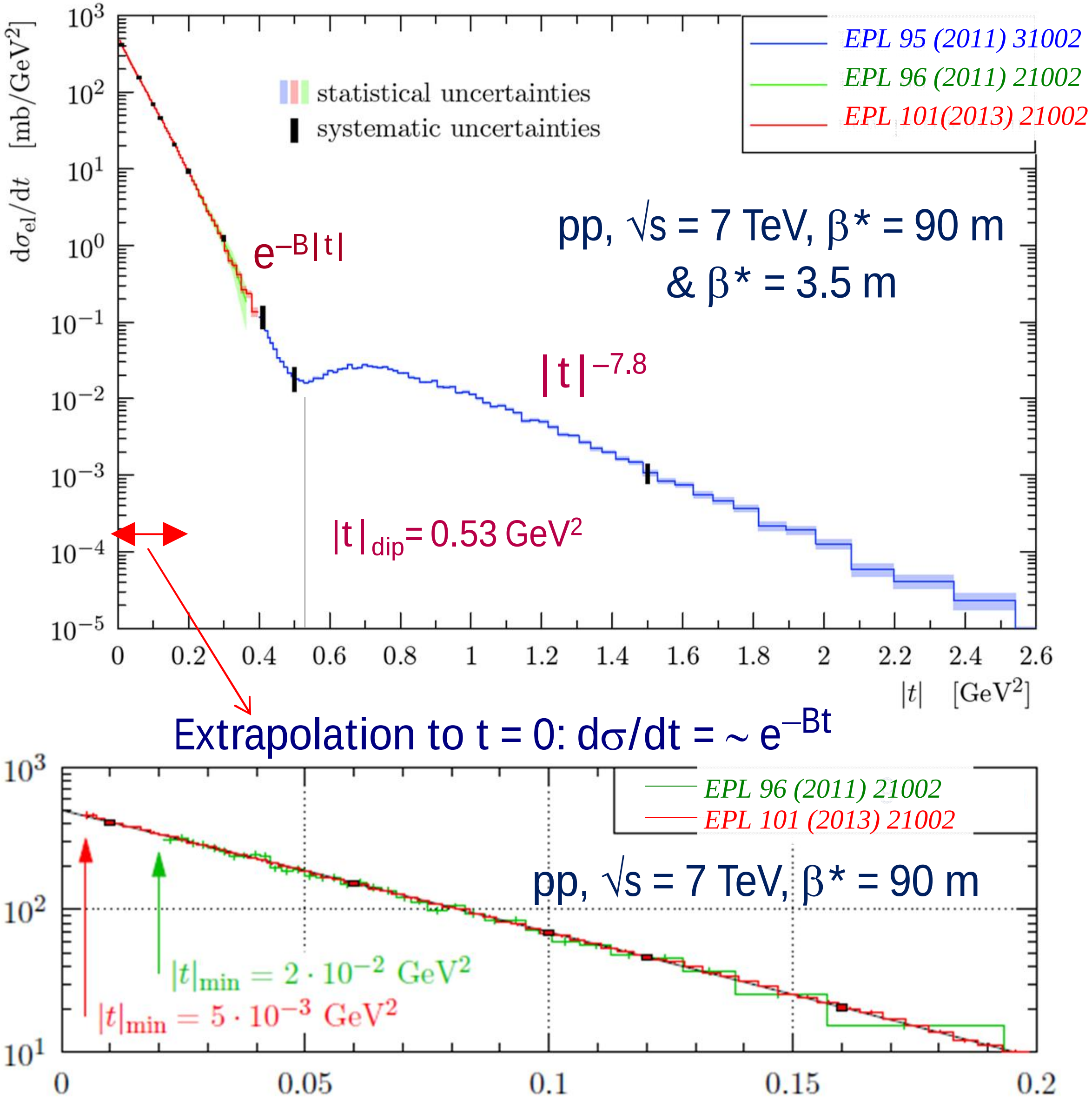
Inelastic telescopes: rapidity gaps



Roman Pots: diffractive protons (di-proton trigger)



Elastic pp scattering cross-section: status I



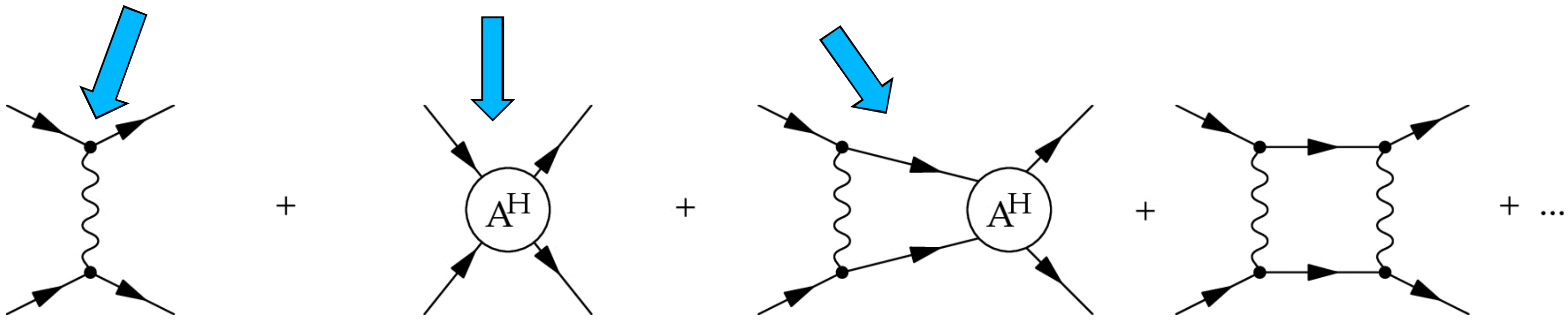
Similar $|t|$ dependence as at ISR (& SppS / Tevatron) with expected changes (smaller $|t|_{dip}$, larger B ...)

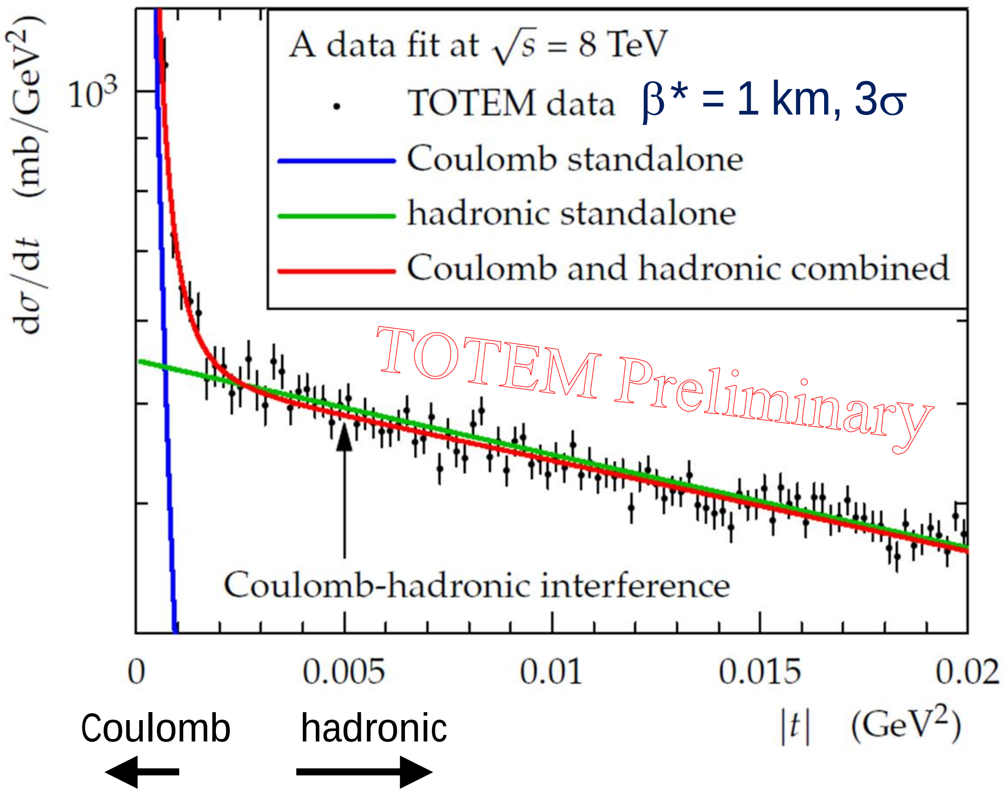
$\Rightarrow$ extract $\sigma_{elastic}$, $d\sigma_{elastic}/dt$ at $t = 0$ (used to determine σ_{total} via optical theorem)

assuming pure hadronic interaction (data not sensitive)!

Elastic pp: Coulomb, hadronic & their interference

$d\sigma/dt \propto |A^{C+H}|^2$ = Coulomb + hadronic + "interference" + ...





– hadronic modulus constrained by measurement of $e^{-B(t)}$

$B(t) = b_1 t + b_2 t^2 + \dots$

N_b = # parameters in exp.

– interference formulae [1,2] (not applicable to all A^H)

– phase of A^H: central or peripheral

⇒ accessible via interference with A^C!

[1] G. B. West and D. R. Jennie, Phys. Rev. 172 (1968)1413.
[2] V. Kundrát and M. Lokajıcek, Z. Phys. C 63 (1994) 619.

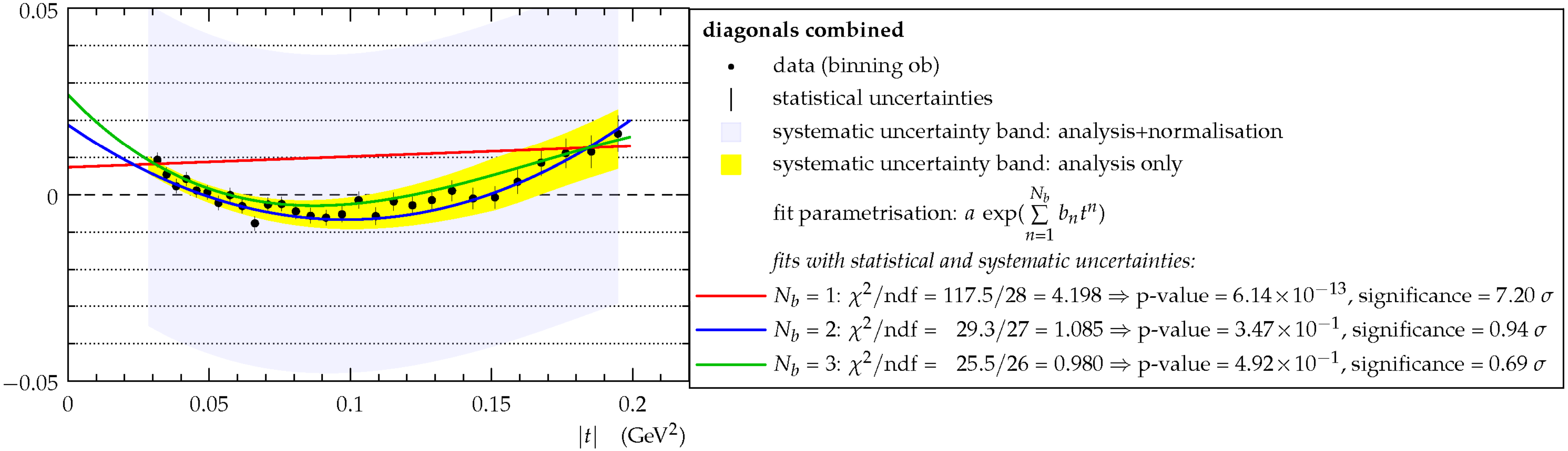
Elastic pp scattering cross-section: status II

At $\sqrt{s}$ = 8 TeV

$\beta^* =$ 1 km: $|t|_{min} \approx 6 \cdot 10^{-4}$ GeV^2, statistics: 0.3

$\beta^* =$ 90 m: $|t|_{min} \approx 2 \cdot 10^{-3}$ GeV^2, statistics: 7 M

Fits: $d\sigma/dt \sim \exp(b_1 t + b_2 t^2 + \ldots)$, N_b parameters in exponent



$\Rightarrow$ purely exponential fit excluded at $> 7\sigma$ significance for A^H for low $|t|$!

First observation in pp, previously only in np (NA6, Nucl. Phys. B234 (1984) 365)

Q1: pure exponential behavior of $A^H \leftrightarrow$ superposition of diagrams?
or coherent effects between fermions and interaction mediators?
Q2: (hadronic phase of) elastic scattering: central or periheral

Better theoretical understanding needed

Total pp cross-section: methods & results

$$\sigma_{tot}^2 = \frac{16\pi}{(1+\rho^2)} \frac{1}{\mathcal{L}} \left(\frac{dN_{el}}{dt} \right)_{t=0}$$

based on elastic scattering ⇒ low mass diffraction independent

σ_{total} = 98.3 mb ± 2.0 mb
EPL 96 (2011) 21002

σ_{total} = 98.6 mb ± 2.3 mb
EPL 101 (2013) 21002

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$$

optical theorem & ρ independent

σ_{total} = 99.1 mb ± 4.3 mb
EPL 101 (2013) 21004

$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{(dN_{el}/dt)_{t=0}}{(N_{el}+N_{inel})}$$

L independent

σ_{total} = 98.1 mb ± 2.4 mb
EPL 101 (2013) 21004

TOTEM @ 7 TeV

Q: Is optical theorem (OT) valid for hadron-hadron scattering?

OT derived for pointlike long-range interaction (γ).
Still valid for short-range interactions of composite objects ?
⇒ valid at least to 3.5 % level (σ_{tot} with & without OT)

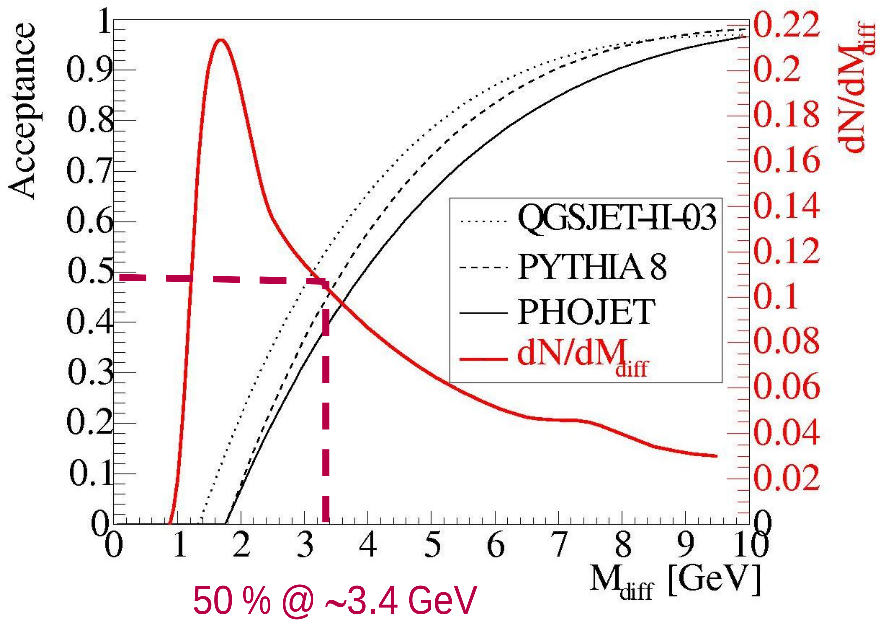
Tests only improved by reduced *L* & low mass diffraction uncertainties
(improvements of *L* determination ?)

Low mass diffraction/disassocation

Diffractive interactions resulting only in final state particles at high |η| (beyond detector acceptance): largest (in mb) of the unknowns @ LHC

Exist data (fixed target, ISR & SppS) but comprehensive picture missing e.g. N* contribution ⇒ severe limitation for all rapidity gap based measurements

SD acceptance for TOTEM T1+T2



50 % @ ~3.4 GeV

TOTEM low mass diffraction (7 TeV):

$\sigma_{inelastic, |\eta| > 6.5} =$

$\sigma_{total} - \sigma_{elastic} - \sigma_{inelastic, |\eta| < 6.5}$

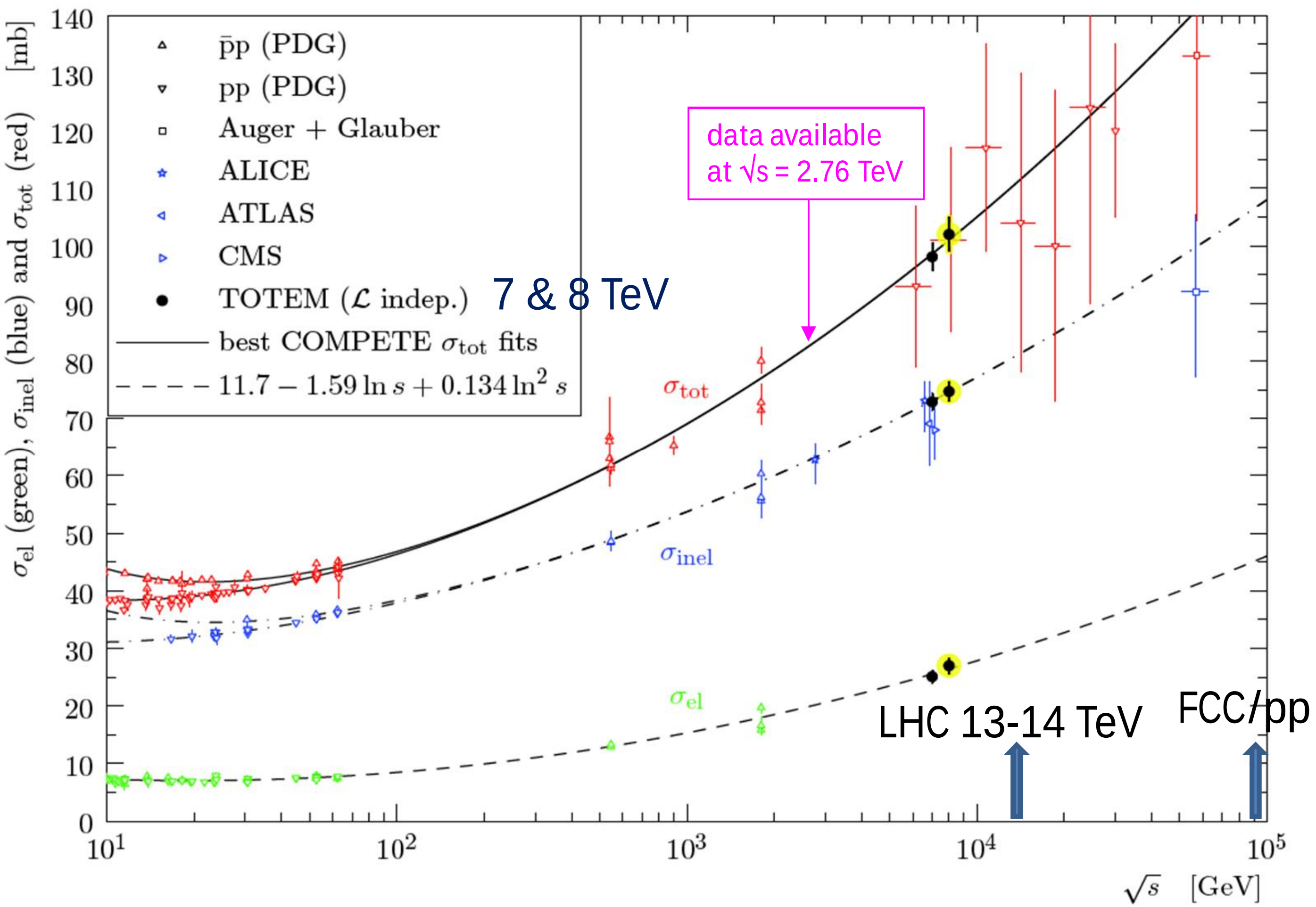
$= 2.62 \pm 2.17$ mb

$\sigma_{inelastic, |\eta| > 6.5} \leq 6.3$ mb @ 95 % CL

EPL 101 (2013) 21003

Need combined p (RPs), n (ZDC's, LHCf) & FSC's ⇒ sofar no success
Probably need fullfledged forward spectrometer at hadron collider !!

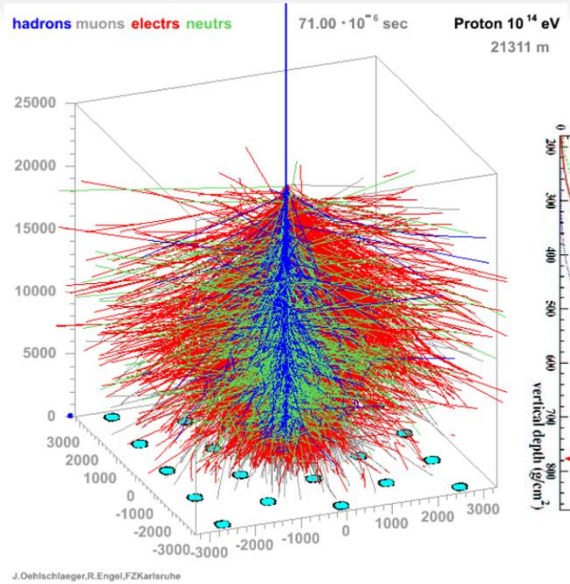
$\sqrt{s}$ behaviour of total & inelastic pp cross-section

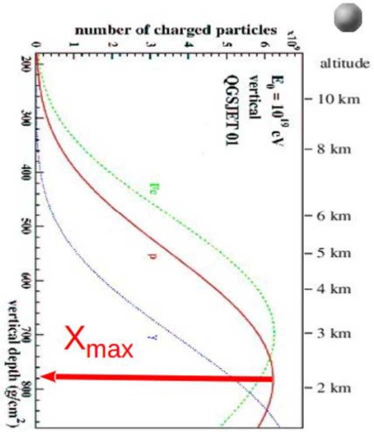


Also important input to cosmic air shower modeling
(together with multiplicity, forward particle flows, …)

Cosmic air shower connection

T. Pierog, QCD & forward physics at the LHC





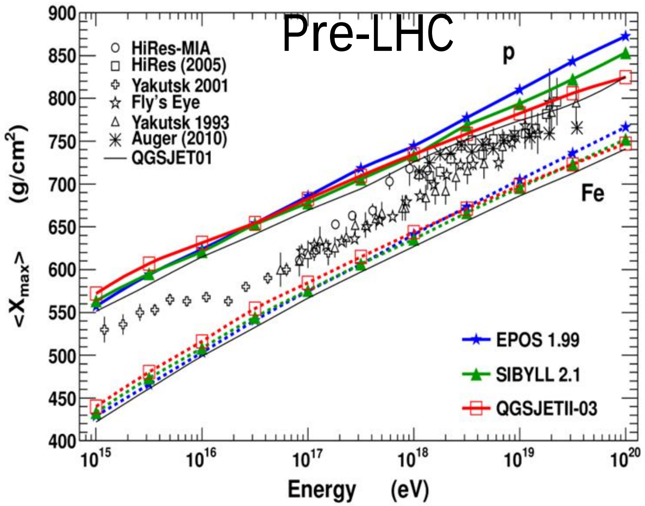
- **Longitudinal Development**
  - ➔ number of particles vs depth

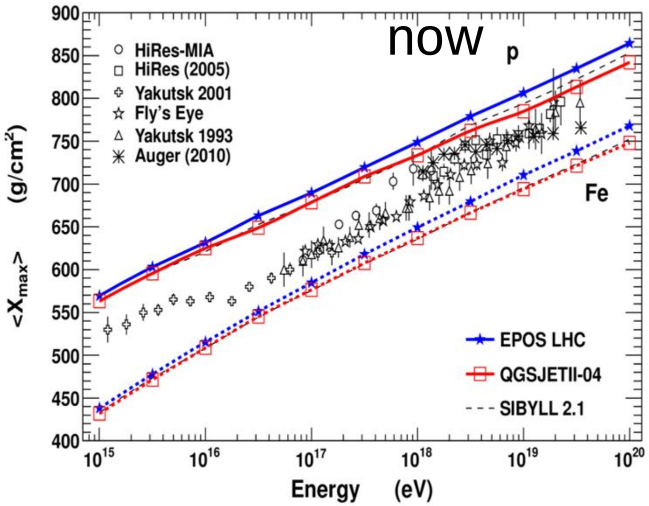
    $$X = \int_h^\infty dz\, \rho(z)$$

  - ➔ Larger number of particles at X_{max}

    For many showers

    - mean : $\langle X_{max} \rangle$
    - fluctuations : RMS X_{max}





Extrapolation to Np(NFe) still limit predictions $\Rightarrow$ pN (pO) collisions@ LHC

Cosmic ray generators better for soft pp interactions than HEP generators !!

Open questions: total, elastic and diffractive cross-section

1. Understanding of low-t behaviour of $\sigma_{elastic}^{pp}$: pure exponential behavior of hadronic amplitude? $\leftrightarrow$ Interference Coulomb-hadronic interference & coherent effects, hadronic phase of elastic scattering: central or periheral

2. Validity of optical theorem for hadron-hadron interactions?

3. Comprehensive picture of low mass diffraction

4. High energy behaviour of σ_{total}^{pp} / $\sigma_{inelastic}^{pp}$? ($\leftrightarrow$ cosmic rays)

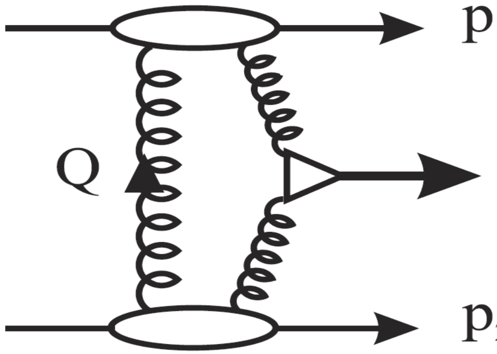
Hard diffraction: present & future

F. Ceccopieri, LTS1

- Impressive knowledge on hard diffraction accumulated by HERA and Tevatron
- This knowledge is quantitative thanks to factorisation theorem: dPDFs NLO pQCD fits of DIS data are available.
- Assume hard scattering factorization : use HERA dPDFs to predict
  - ⋆ dijet in DIS: data/NLO $\simeq 1$
  - ⋆ dijet in PHP: debated data/NLO $\simeq 0.5 - 1$
  - ⋆ dijet or $W^{\pm}$ in $p\bar{p}$ at Tevatron: data/NLO $\simeq 0.1$
- The way hard scattering factorisation fails opens windows on NP physics
- Present and near future : discovery-like program at hadron collider:
  - how factorisation is broken : use diffractive DY as clean benchmark process
  - Can we recover approximate predictivity (just K-factor or more complex scenarios)?
- Distant future : precision-like program in future ep machines:
  - Solve the puzzle in diff.PHP and Improve in the DIS low $1 < Q^2 < 10$ GeV^2 regime
  - Study the interplays of hard diffraction with saturation and low-x physics

Q: Understanding factorization breaking in hard diffraction ($l^{\pm}h \leftrightarrow hh$)

Central exclusive production (CEP)



$\boxed{M^2 = \xi_1\ \xi_2\ s}$

$$\boxed{y_X = \frac{1}{2}\ln\frac{\xi_1}{\xi_2}}$$

also $\gamma\gamma$ fusion & photoproduction

gg collider !

exchange of colour singlets with vacuum quantum numbers $\Rightarrow$ Selection rules for system X: $J^{PC} = 0^{++}, 2^{++}$

X = 0^{++} & 2^{++} (light q, c & b) resonances, jets,?....

M= $m_{\pi\pi}$ – ~ 1 TeV,

σ = O(μb) – O(fb)

<u>With proton tagging:</u>

Normal LHC runs: M(pp) acceptance > 350 GeV

$\Rightarrow$ σ's small (fb), need high lumi, only accessible with CT PPS & AFP

Special runs: all M(pp), $\mu \sim 0.05$ - 0.5 $\Rightarrow$ O(0.1-10 pb^{-1}/day)

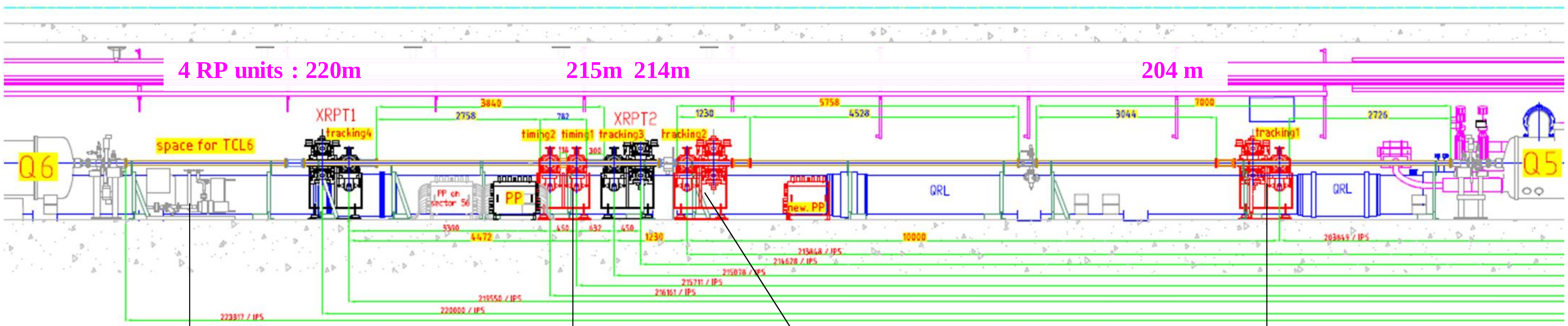
CMS & TOTEM common runs: if $\mu \sim 0.5$ need timing in vertical TOTEM RPs

<u>With rapidity gaps (also ALICE, ATLAS & CMS):</u>

LHCb in normal LHC runs, σ's ($\geq$ fb), improved with Herschel .

(CMS-)TOTEM RP system consolidation & upgrade

Mechanics / infrastructure in 2014 (LS1),
timing sensors / Si pixel detectors later (during short technical stops)



Install collimator
to protect Q6

Infrastructure to install
2 new horizontal RP

RP147 (fully equipped) relocated at
203-213 m 1 unit rotated by 8 degrees

Allow insertion of (horizontal) RPs closer to beam in high intensity scenario
→ improved ξ acceptance

To host timing sensors (quartz bars or solid state sensors)

Long lever arm (~15m) improves angular resolution (until beam divergence limit)

Si-strip detectors rotated to improve multitrack event reconstruction (beam halo pileup, background)

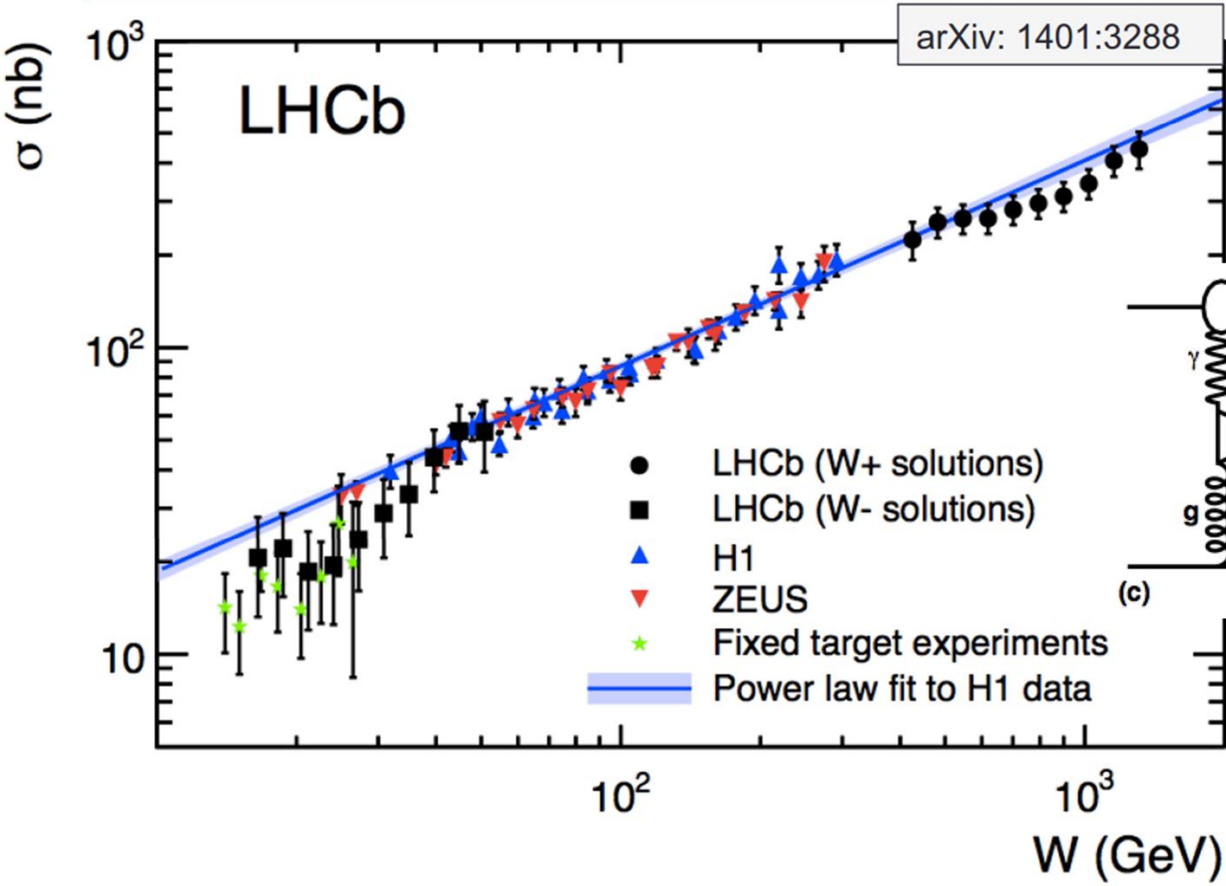
- RP system made of 4 RP units/arm, each with 2 vert. + 1 horiz. RP with μstrip detectors
- CT PPS: existing μstrip detectors in horizontal RPs replaced by silicon pixel trackers + addition of 2 new cylindrical horizontal RP with timing sensors (~10 ps) for high luminosity running
- Timing in TOTEM vertical RP's: solid state timing sensors (~50 ps) for special runs with $\mu \sim 0.5$

CEP J/ψ

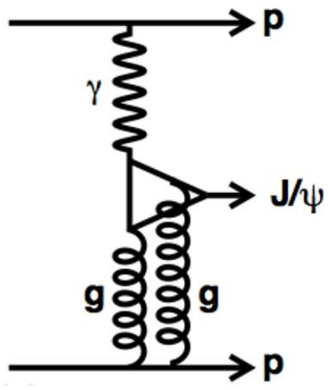
Photo-production cross-section

Measure   Plot   HERA

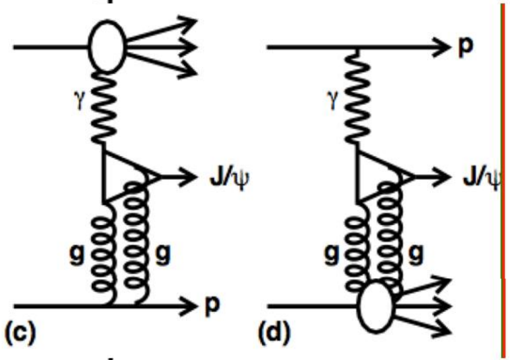
$$\left.\frac{d\sigma}{dy}\right|_{pp\to pJ/\psi p} = r_+ k_+ \frac{dn}{dk_+}\sigma_{\gamma p\to J/\psi p}(W_+) + r_- k_- \frac{dn}{dk_-}\sigma_{\gamma p\to J/\psi p}(W_-)$$



Signal:



Backgrounds:



Also ALICE did CEP J/ψ

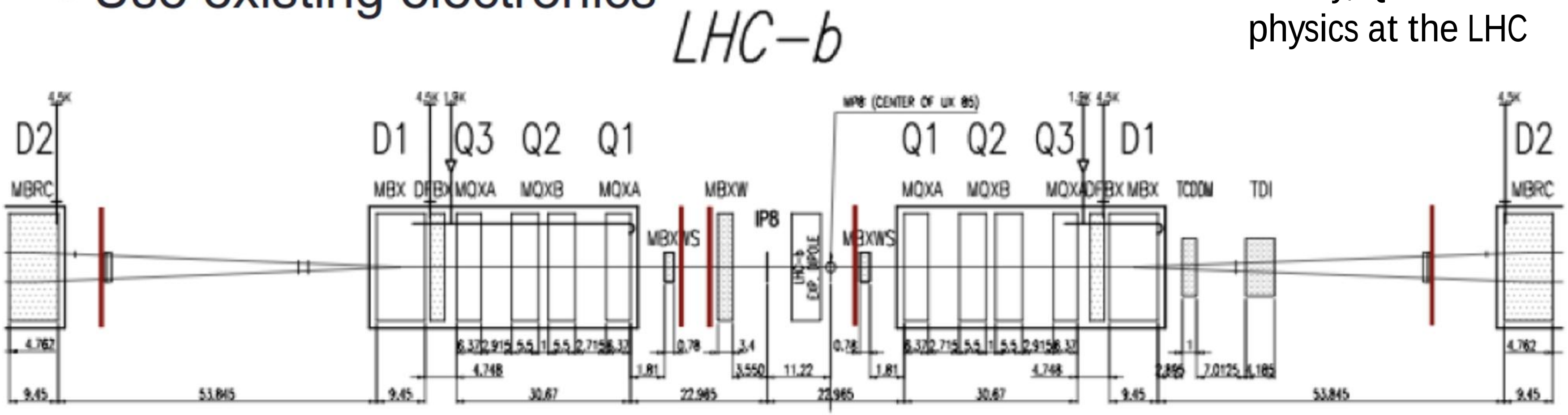
Deviation from pure power-law. i.e. NLO required or only power-law for $W>W_0$

LHCb Herschel

High rapidity shower counters for LHCb

- Increase rapidity gap with scintillators in forward region
- Use existing electronics

R. McNulty, QCD & forward physics at the LHC



Installed during LS1

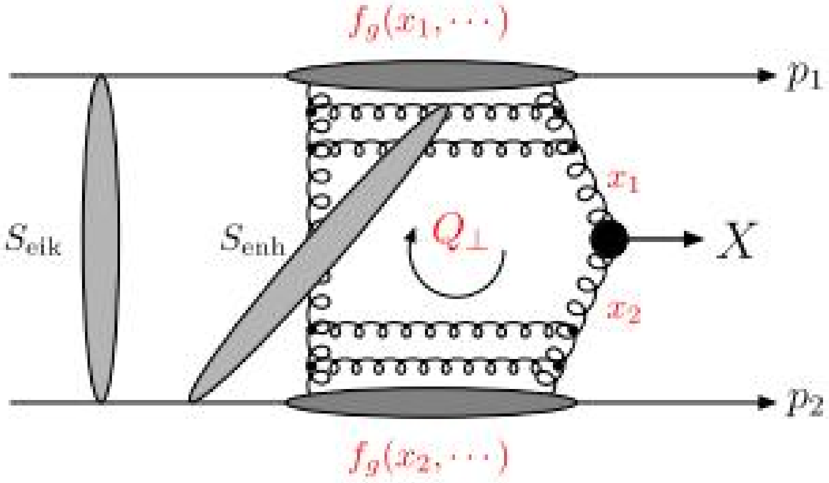
Left
1. z ~ -7.5 m (after MBXW)
2. z ~ -19m (before MBXWS)
3. z ~ -114m (after BRANS)

Right
1. z ~ 19 m (close to MBXWS)
2. z ~ 114m (after BRANS)

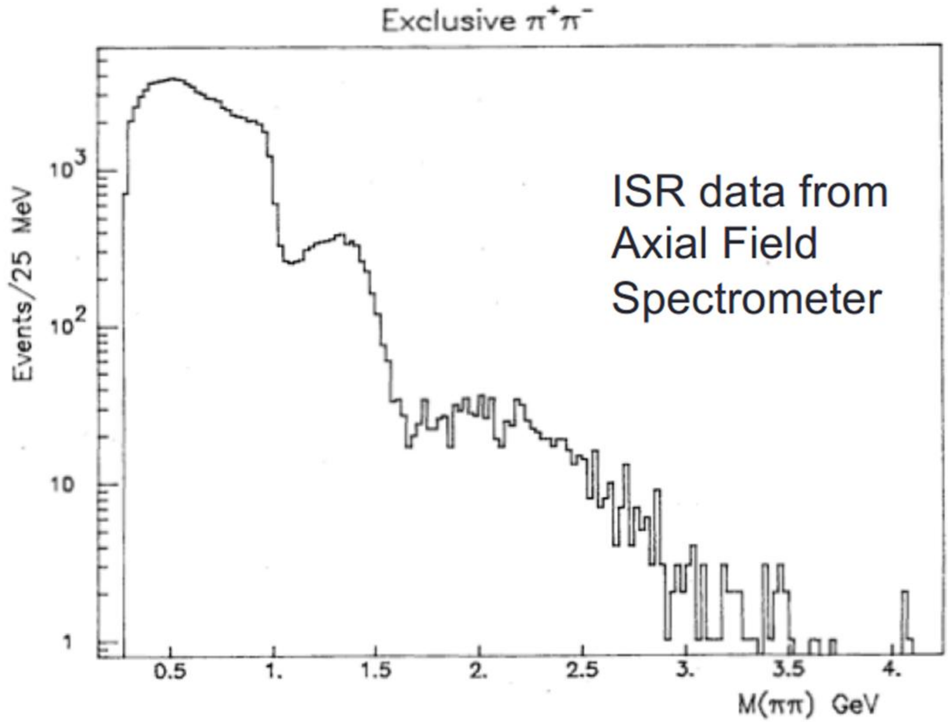
First simulations suggest veto region for charged and neutral particles can be extended to include $5<|\eta|<8$

CEP low mass states & glueballs

KHARYS



X = low mass resonance /meson pair



LHC an excellent place to study CEP low mass states:

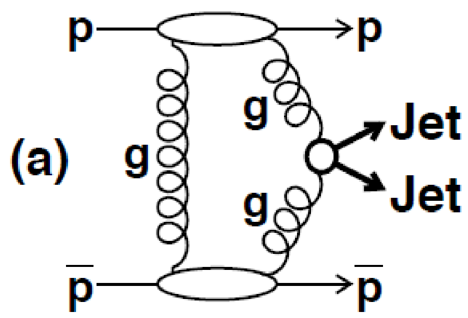
- small p_T's $\Rightarrow$ $\Delta m \sim 10$ MeV from tracking (CMS-TOTEM & LHCb)
- excellent angular coverage (CMS-TOTEM & LHCb)
- proton tagging in special runs (CMS-TOTEM)

Pomeron = virtual glue ball ? $\Rightarrow$ likely to produce glue balls in Pomeron fusion

CEP jets

cross-sections, 3j/2j ratio, gluon jet studies

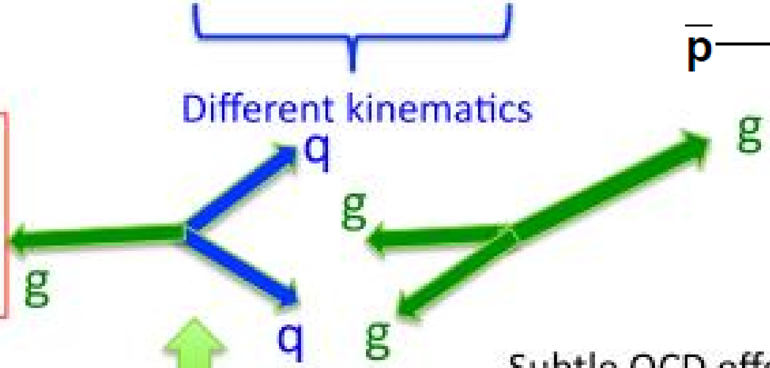
Durham group (KHARYS MC)



CDF Observed X = JJ at √s = 1.96 TeV to E_T = 30 GeV

At LEP: e+e- → Z → 2 jets (q-qbar) or 3 jets (q-qbar-g)

At LHC: IP + IP → 2 jets (g-g) or 3 jets (q-qbar-g) OR (g-g-g)



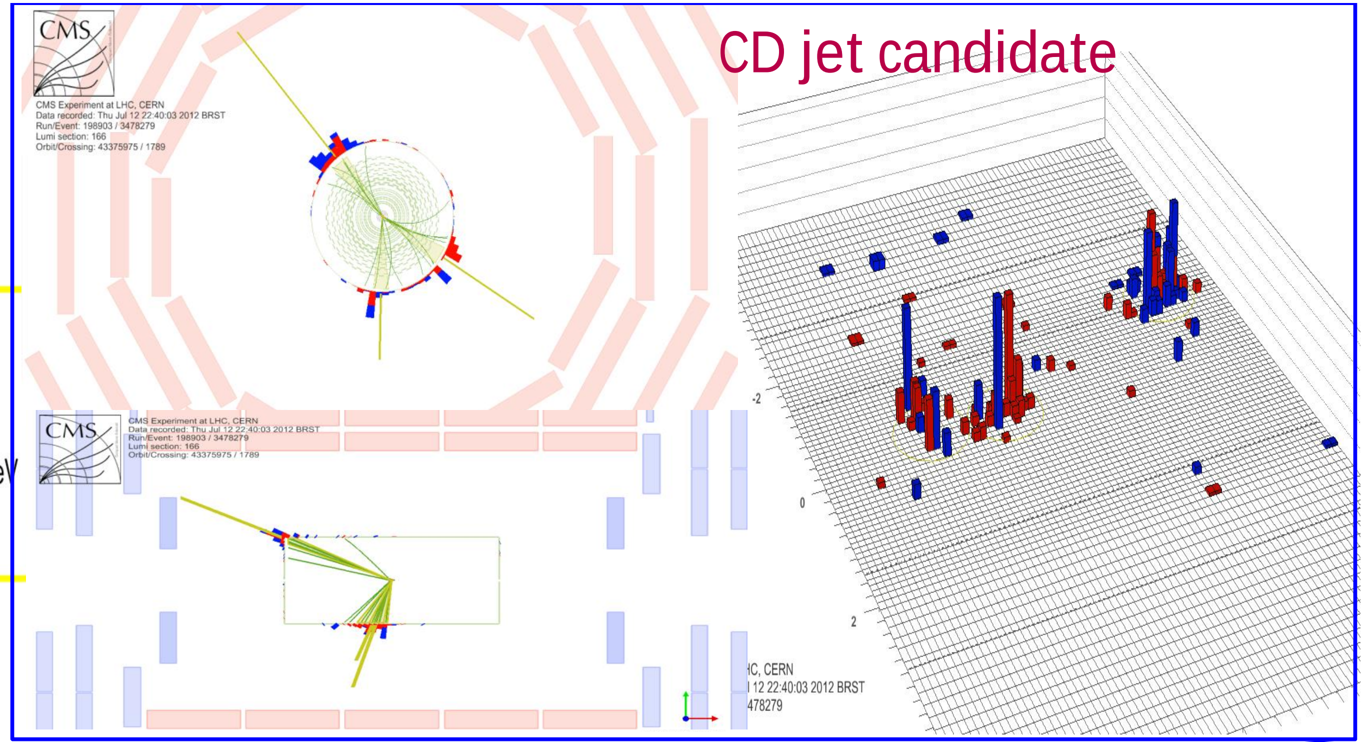
99% of exclusive dijets are g-g (unique) 1% are b-bbar
→ uu, dd, ss, cc suppressed by $[m(q)/m(JJ)]^2$ (Durham theory gp)

Democratic so 1/5 each quark type:
20% b-bbar 20% c-cbar, ...

Subtle QCD effects:
No gluon radiation (Sudakov)
No other parton collisions
Test spin rule Jz = 0
Interplay of pQCD and npQCD
Distant relation to elastic scattering

Standard LHC runs: M(pp) acceptance > 350 GeV
⇒ σ's small (fb), need high lumi, only accessible with CT PPS & AFP

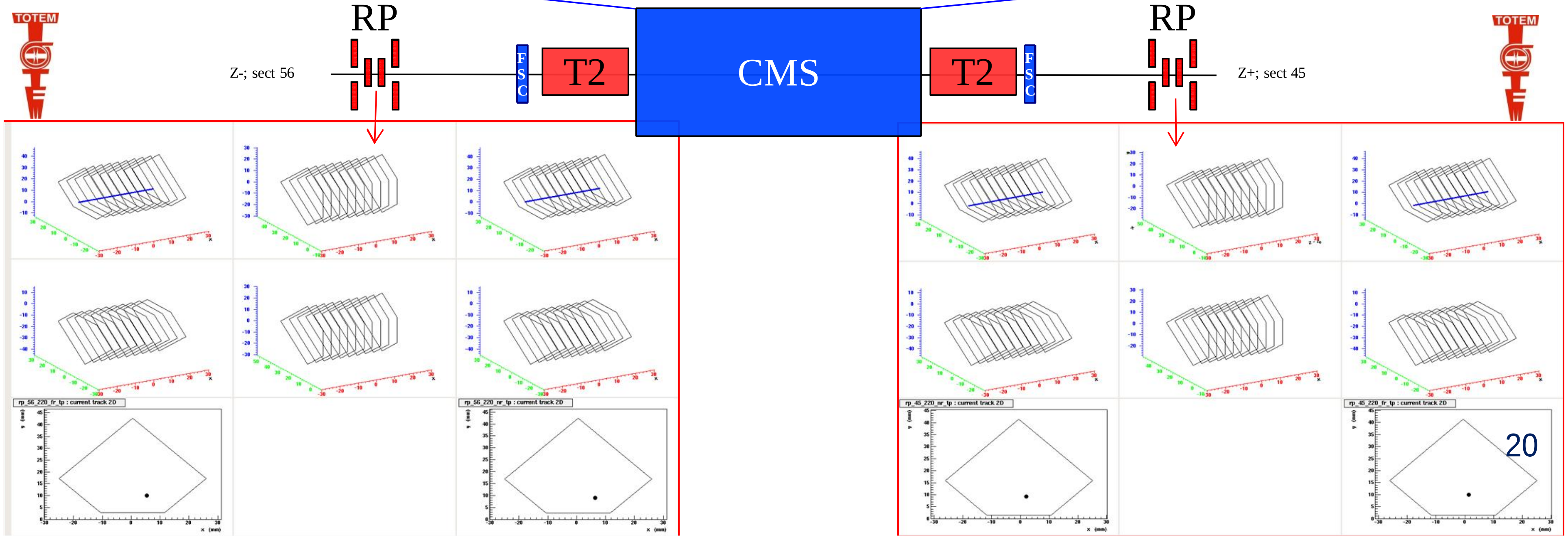
Special runs: all M(pp), μ ~ 0.5 & 1k bunches ⇒ O(10 pb^{-1})
σ(M(pp) > 75 GeV) = ~100 pb @ s = 13 TeV (KHARYS)
only accessible with timing detectors in vertical TOTEM RPs



CMS + TOTEM 90m β^*
Run/Event 198903/3478279
Jets E_T = 65,45,27 GeV

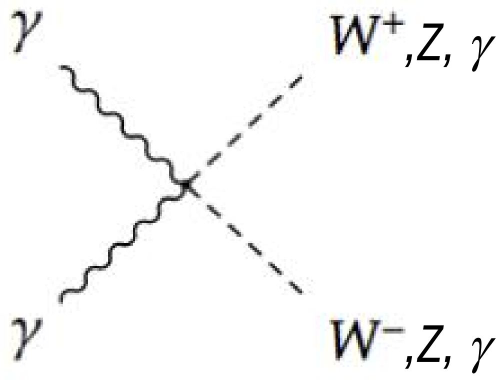
MM(pp) = 244 GeV; M(CMS) = 219 GeV
Σp_T(CMS) = 3.4 GeV
FSC empty both sides

M(pp) = 244 GeV
≈ M(central)
$\xi_1 = 0.1$ $\xi_2 = 0.01$

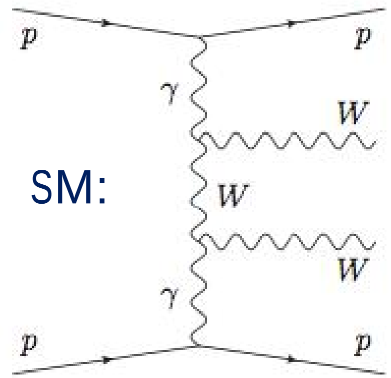


Anomalous Quartic Gauge couplings

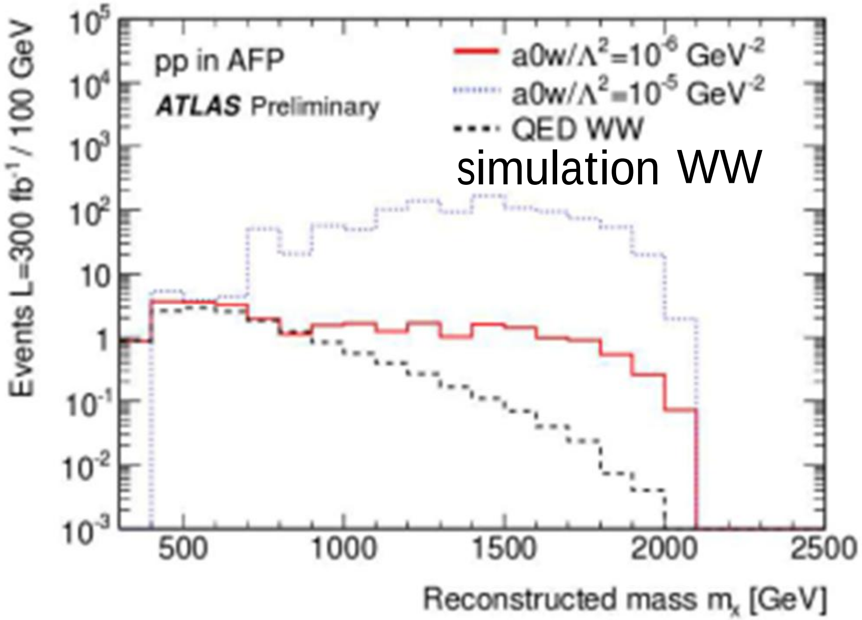
Search for BSM physics: sensitivity better by order(s) of magnitude with protons

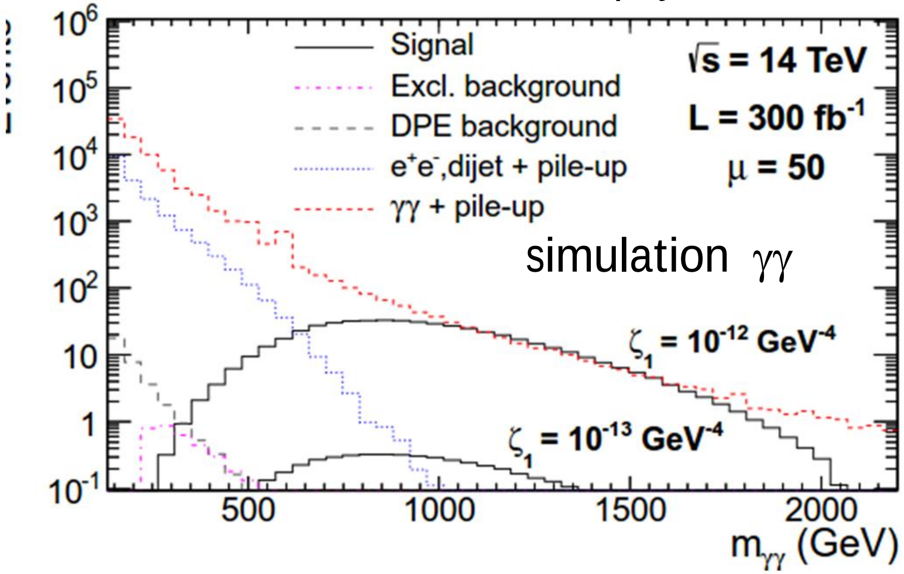


SM:



M. Sampert, QCD & forward physics at the LHC





Open questions: Diffraction & central exclusive production (CEP)

1. Understanding factorisation breaking in hard diffraction?
2. Existence of glueballs (or gluon rich-resonances) & their hierarchy?
3. $\gamma\gamma$ fusion as probe for beyond SM physics ?

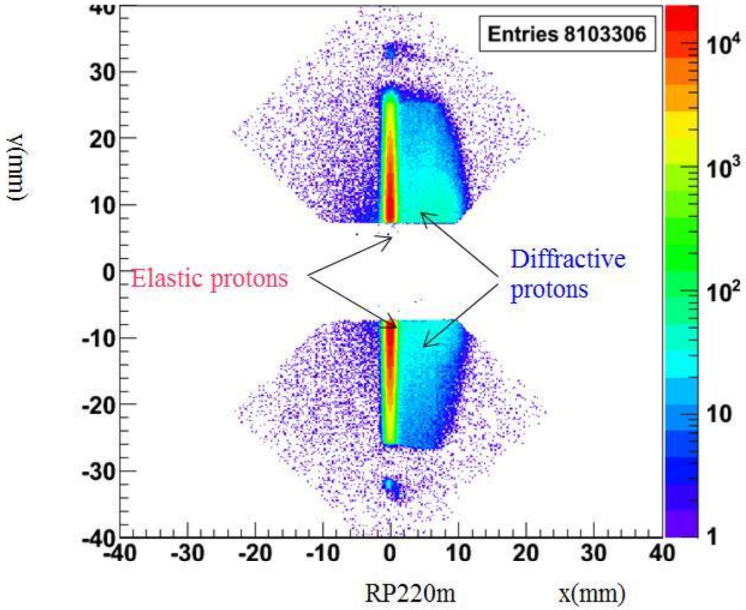
Summary

Total, elastic and diffractive cross-sections:

- Wide physics range
- Many open issues
- Instrumental upgrades of LHC detectors crucial for exploitation of diffractive potential especially CEP processes

Backup

Performances: diffractive protons measurements

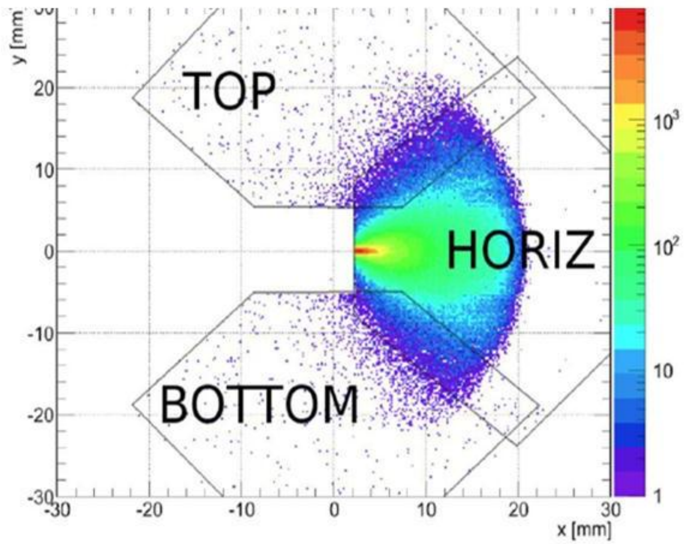


Raw hit distribution of leading protons
Optics β^* = 90m; Run July 2012 (CMS+TOTEM run)

$|t| > 0.02$ GeV^2 (RP at $10\sigma_{y,\,beam}$), all ξ

Acceptance: soft CD (2 protons tagged) ~ 25 %

s(ξ) ~ 0.8% (0.3% with CMS vertex)
s(M) ~ 50 GeV (20 GeV with CMS vertex)



Simulated hit distribution of leading protons at low β^*

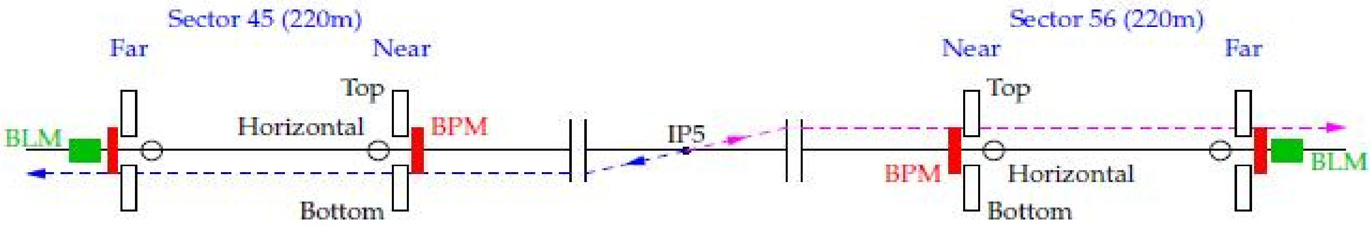
$\xi > 0.03$ (RP at $15\sigma_{x,\,beam}$), all t

Acceptance: soft CD (2 protons tagged) ~ 2 %

s(ξ) ~ 0.1-0.2%
s(M) ~ (0.02-0.03)M

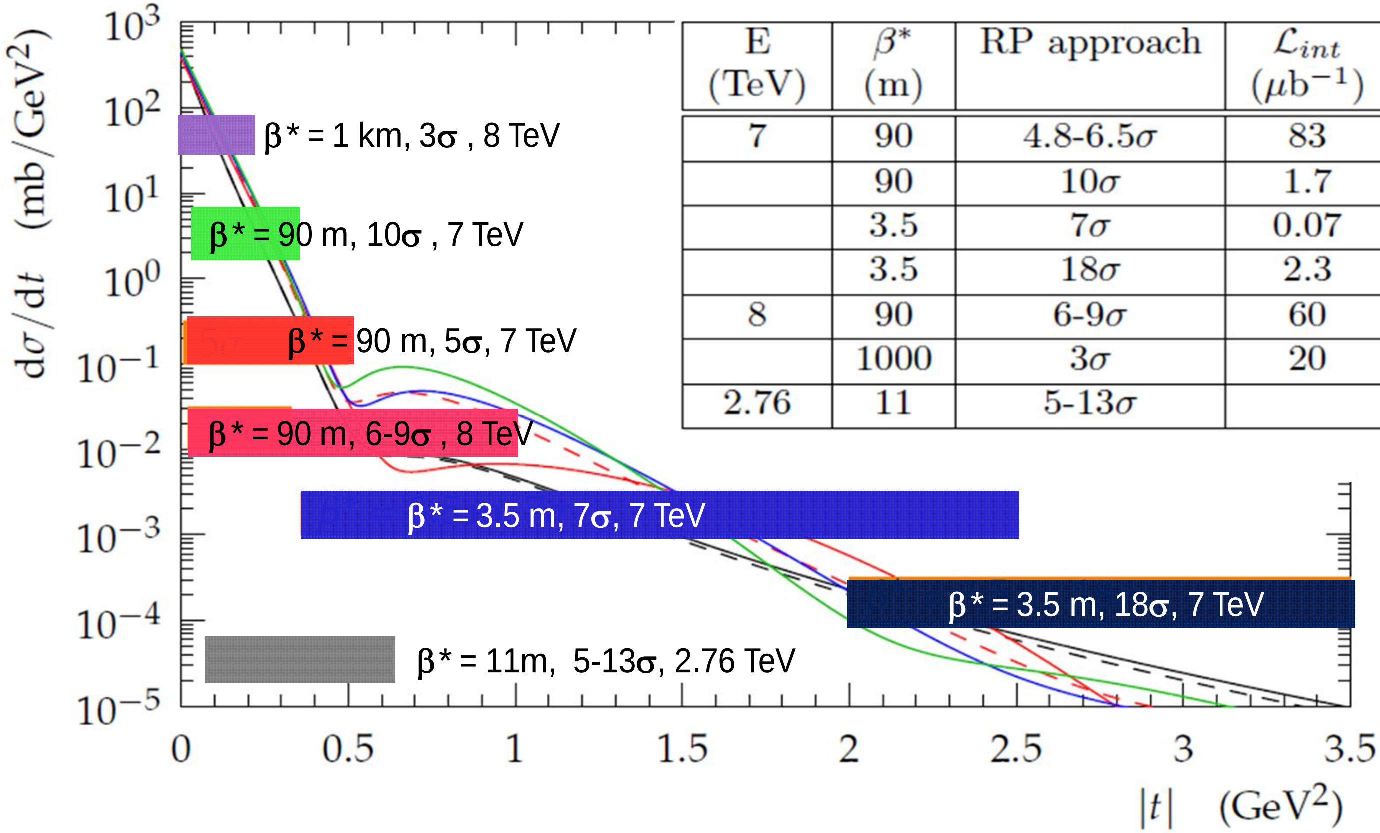
Elastic pp scattering: selection & data sets

Selected based on topology, low |ξ|, collinearity, & vertex



Key issues: RP alignment & optics

Data sets at different conditions to measure elastics over wide t-range including very low |t|



E (TeV)	β^* (m)	RP approach	$\mathcal{L}_{int}$ (μb^{-1})	t range (GeV^2)	Elastic events
7	90	4.8-6.5σ	83	$7\cdot10^{-3}$ - 0.5	1M
	90	10σ	1.7	0.02 - 0.4	14k
	3.5	7σ	0.07	0.36 - 3	66k
	3.5	18σ	2.3	2 - 3.5	10k
8	90	6-9σ	60	0.01 - 1	8M
	1000	3σ	20	$6\cdot10^{-4}$ - 0.2	0.4M
2.76	11	5-13σ		0.05-0.6	45k

Show results from data sets indicated by arrows

Run scenarios

- β^* = 90 m & low lumi: $N_b \le 156$, $N_p/b \sim (0.5\text{-}0.7)\cdot 10^{11}$ (no xangle) $\Rightarrow \mu \sim$ 0.05-0.1, $L \sim 10^{30}$ cm^{-2} s^{-1}, ~0.1-0.2 pb^{-1}/day

  - total cross-section, elastic scattering, soft diffraction, charged multiplicity, SD jets (low p_T)...

- β^* = 90 m & medium lumi: $N_b \approx 1000$, $N_p/b \sim 1.5\cdot 10^{11}$ (100 μrad xangle) $\Rightarrow \mu \sim 0.5$, $L \sim 10^{32}$ cm^{-2} s^{-1}, ~5 pb^{-1}/day

  - CD & CEP jets (low p_T), CD missing mass topology, CD exclusive low mass resonances/meson pairs, CEP $\gamma\gamma$, SD J/ψ, SD jets (medium p_T)...

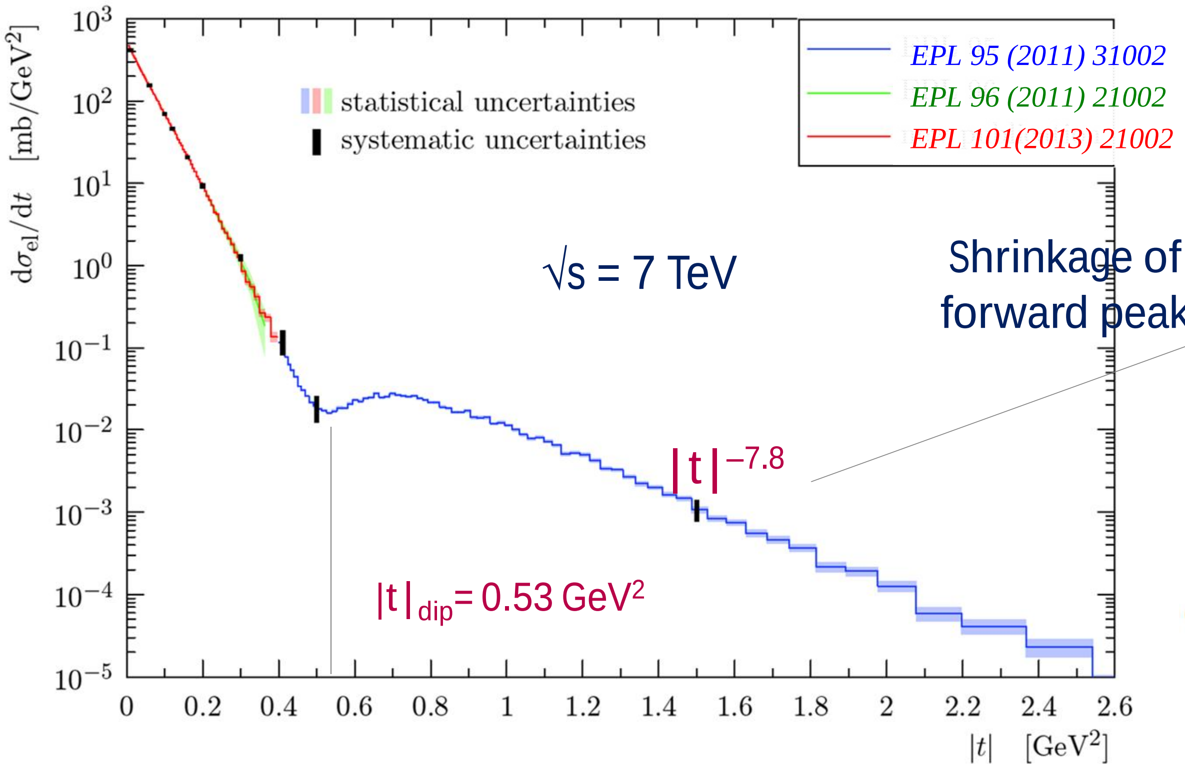
  need precise timing in vertical RPs

- Low β^* & high lumi: $N_b \approx 2500\text{-}2800$, $N_p/b \sim (1.2\text{-}1.5)\cdot 10^{11}$ (290 μrad xangle) $\Rightarrow$ $\mu \sim 30\text{-}50$, $L \sim (1\text{-}2)\cdot 10^{34}$ cm^{-2} s^{-1}, ~1-1.5 fb^{-1}/day

  - CEP jets (high p_T and M_{diff}), vector boson (W, Z) pairs and search for anomalous couplings, CD missing mass topology(?)..

  need precise timing + Si pixel in horizontal RPs $\Rightarrow$ CMS/TOTEM PPS

Elastic pp scattering: implications

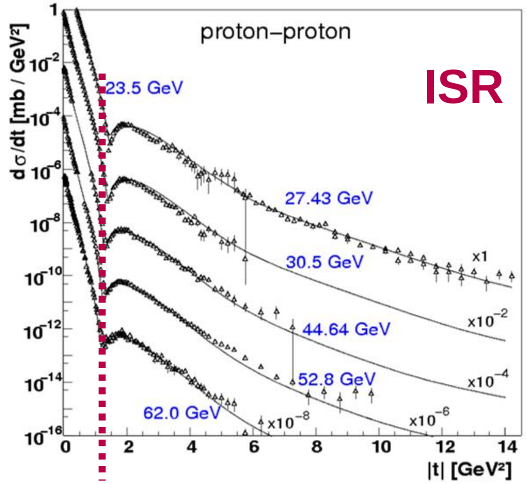


$\sqrt{s}$ = 7 TeV

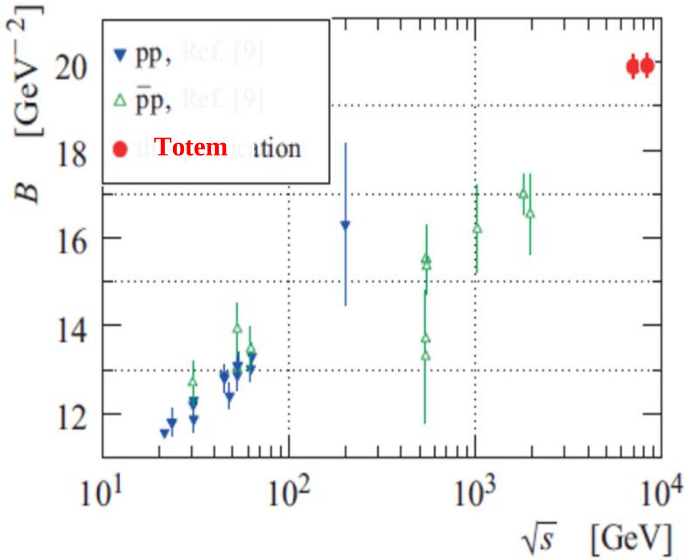
$|t|^{-7.8}$

$|t|_{dip}$= 0.53 GeV^2

Shrinkage of forward peak



~1.5 GeV^2



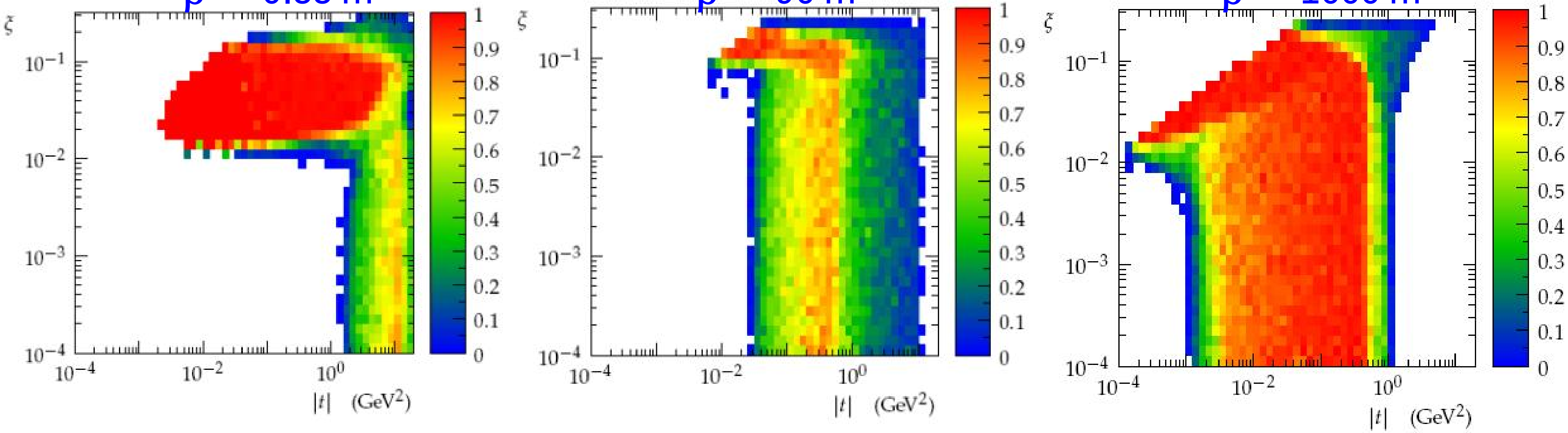
$d\sigma/dt \sim e^{-B|t|}$

Increase of B slope with collision energy

LHC Optics & proton acceptance

$t \approx -p^2\, \Theta^{*\,2}$: four-momentum transfer squared; $\xi = \Delta p/p$: fractional momentum loss

β* = 0.55 m β* = 90 m β* = 1000 m



> 10^{33} cm^{-2} s^{-1} ← $\boxed{L \propto \frac{1}{\beta^*}}$ → ~10^{27} cm^{-2} s^{-1}

Diffraction:
ξ > ~0.03, low cross-section processes (hard diffraction)
Elastic scattering: large |t|

Diffraction: all ξ if |t| > ~10^{-2} GeV^2, soft & semi-hard diffraction
Elastic scattering:
low to mid |t|
Total cross-Section

Elastic scattering:
very low |t|,
Coulomb-Nuclear Interference
Total cross-Section