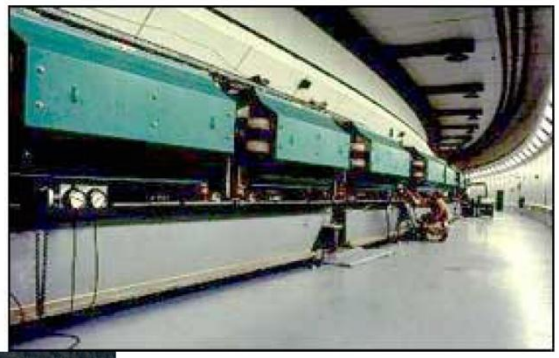
Fizika čestica na sudarivačima

II. DRELL-YAN-ove PRODUKCIJE i HADRONSKI SUDARIVAČI

- PROTON - AT. JEZGRE
- PROTON - ANTIPROTON
- PROTON - PROTON (LHC)

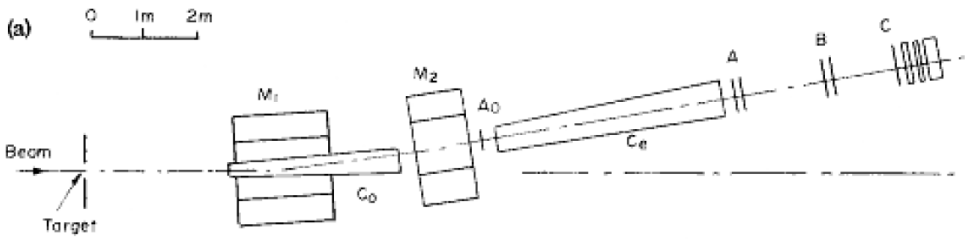
DRELL-YAN-ove PRODUKCIJE

Brookhaven National Lab
Alternating Gradient Synchrotron



The Process: p + Be → e^+ e^- X

very narrow width
⇒ long lifetime



at BNL AGS

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen
J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technolog
Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \rightarrow e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

This experiment is part of a large program to daily with a thin Al foil. The beam spot

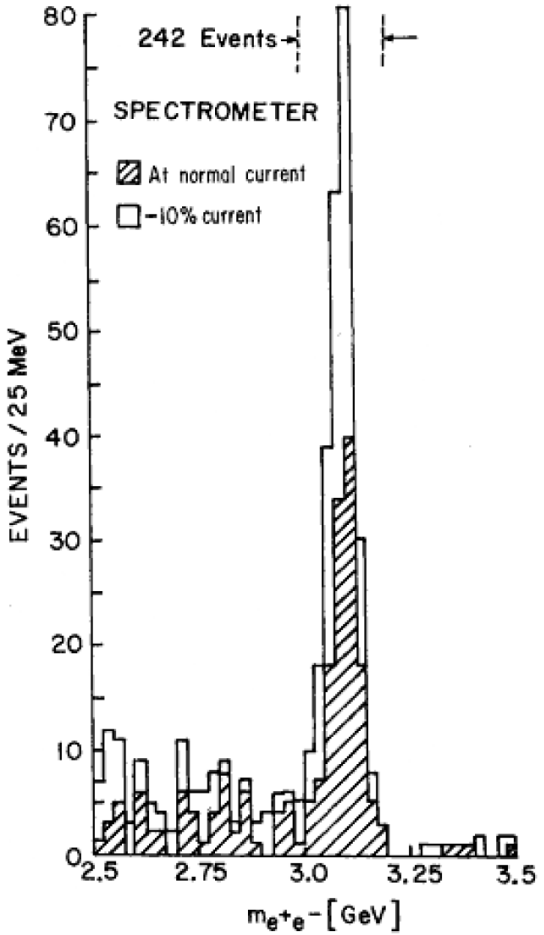
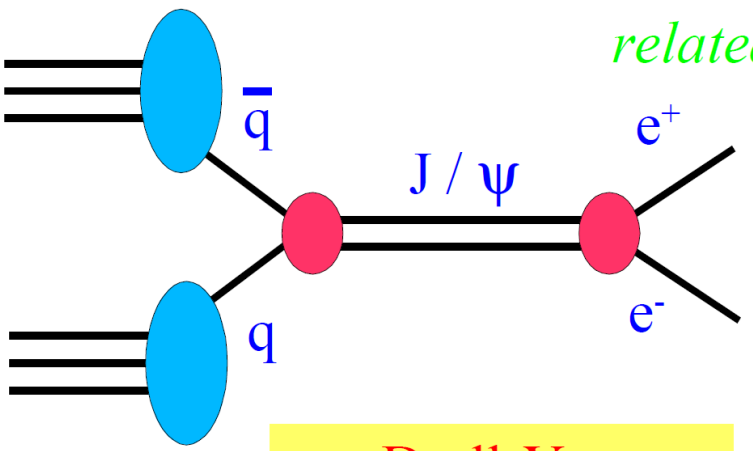
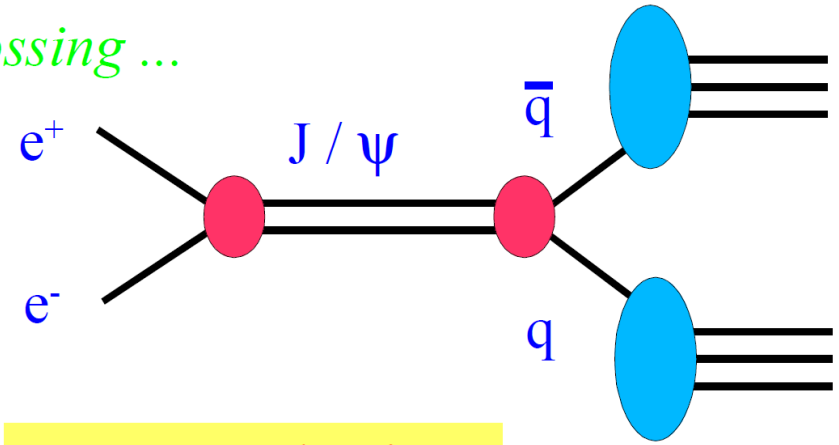


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

related by crossing ...





Drell-Yan
Brookhaven AGS

e^+e^- Production
SLAC SPEAR
Frascati ADONE

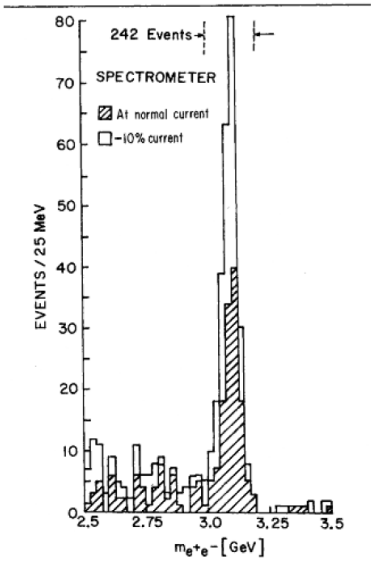
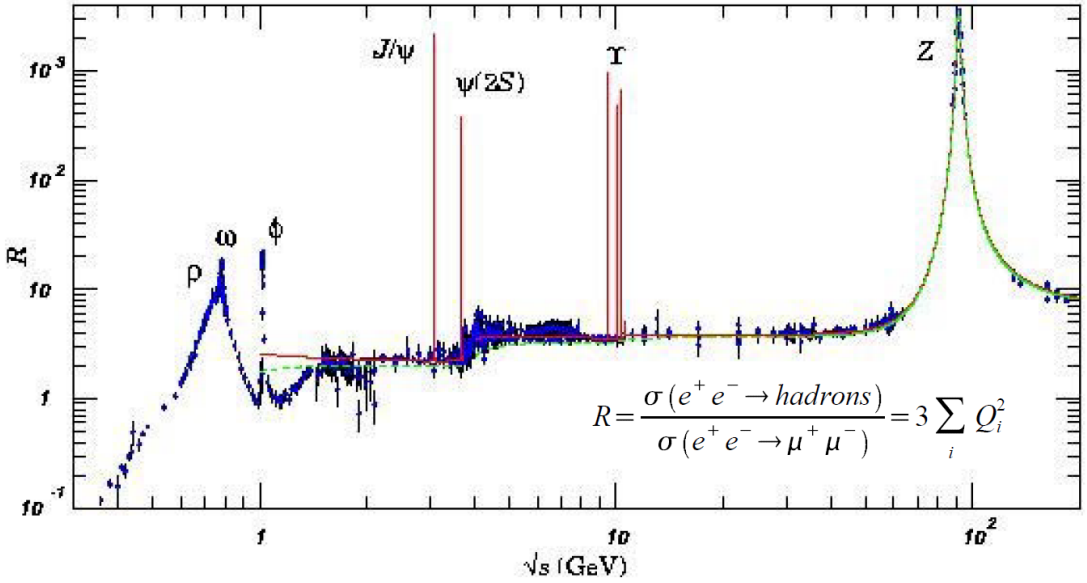


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.



PRODUKCIJE NOVIH STANJA

1974: The J/Psi (charm) discovery $p+N \rightarrow J/\psi$

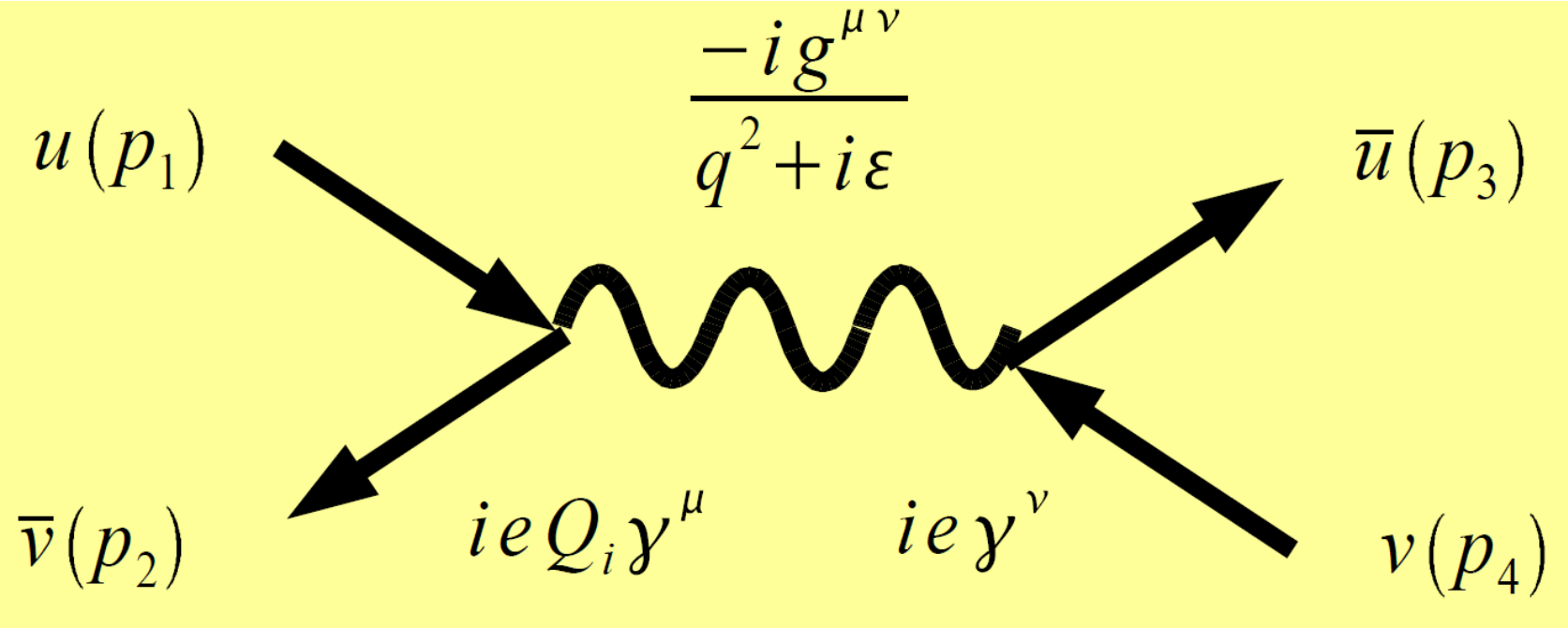
... 1976 Nobel Prize

1977: The Upsilon (bottom) discovery $p+N \rightarrow \Upsilon$

1983: The W and Z discovery $p + \overline{p} \rightarrow W/Z$

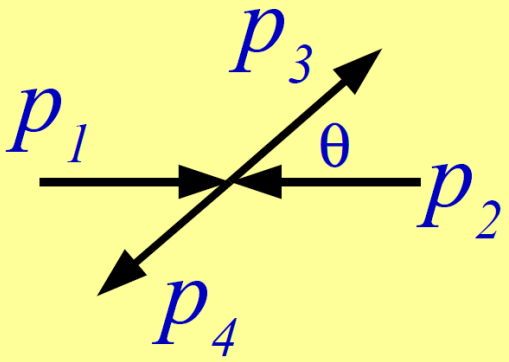
... 1984 Nobel Prize

RAČUN DRELL-YAN-ove PRODUKCIJE FOTONOM



$$-iM = iQ_i \frac{e^2}{q^2} \{\bar{v}(p_2)\gamma^\mu u(p_1)\} \{\bar{u}(p_3)\gamma_\mu v(p_4)\}$$

U SUSTAVU PARTONA



$$p_1^2 = p_2^2 = p_3^2 = p_4^2 = 0$$

$$p_1 = \frac{\sqrt{\hat{s}}}{2}(1,0,0,+1)$$

$$p_2 = \frac{\sqrt{\hat{s}}}{2}(1,0,0,-1)$$

$$p_3 = \frac{\sqrt{\hat{s}}}{2}\left(1,+\sin(\theta),0,+\cos(\theta)\right)$$

$$p_4 = \frac{\sqrt{\hat{s}}}{2}\left(1,-\sin(\theta),0,-\cos(\theta)\right)$$

$$\overline{|M|^2} = Q_i^2\,\alpha^2\,\frac{2^5\pi^2}{3}\left(\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)$$

$$q^2 = (p_1+p_2)^2 = \hat{s}$$

$$\alpha = \frac{e^2}{4\pi}$$

$$d\hat{\sigma} \simeq \frac{1}{2\hat{s}} \overline{|M|^2} \, d\Gamma$$

$$d\Gamma = \frac{d\cos(\theta)}{16\pi}$$

$$\frac{d\hat{\sigma}}{d\cos(\theta)} = Q_i^2 \alpha^2 \frac{\pi}{6} \frac{1}{\hat{s}} \left(1+\cos^2(\theta)\right)$$

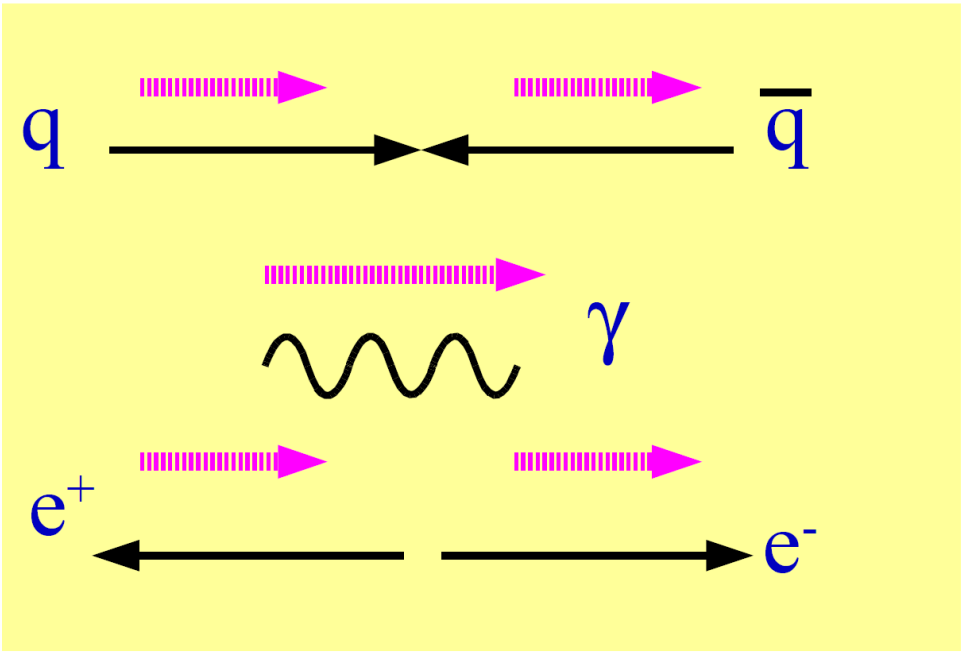
$$\hat{\sigma} = \frac{4\pi\alpha^2}{9\hat{s}} Q_i^2 \equiv \hat{\sigma}_0$$

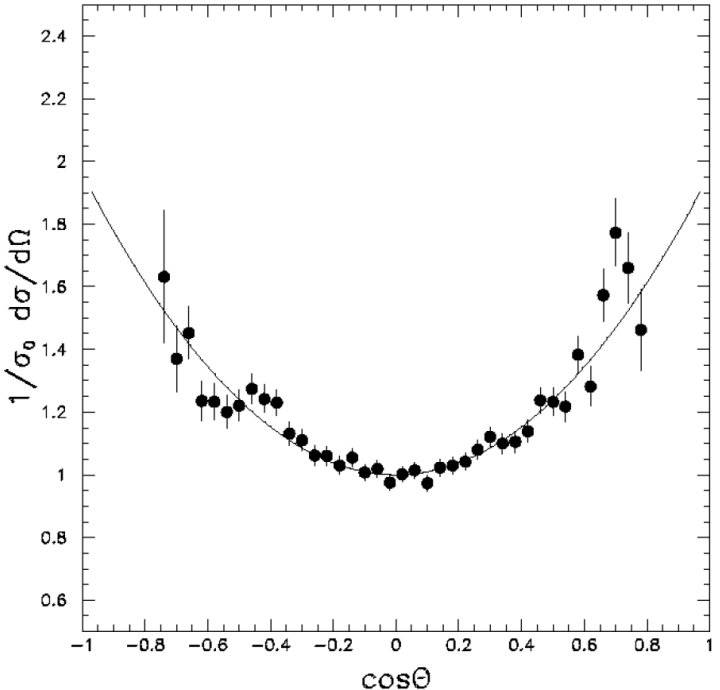
IZMJENA ČESTICE SPINA 1

Observe, the angular dependence: $q + \bar{q} \rightarrow e^+ + e^-$

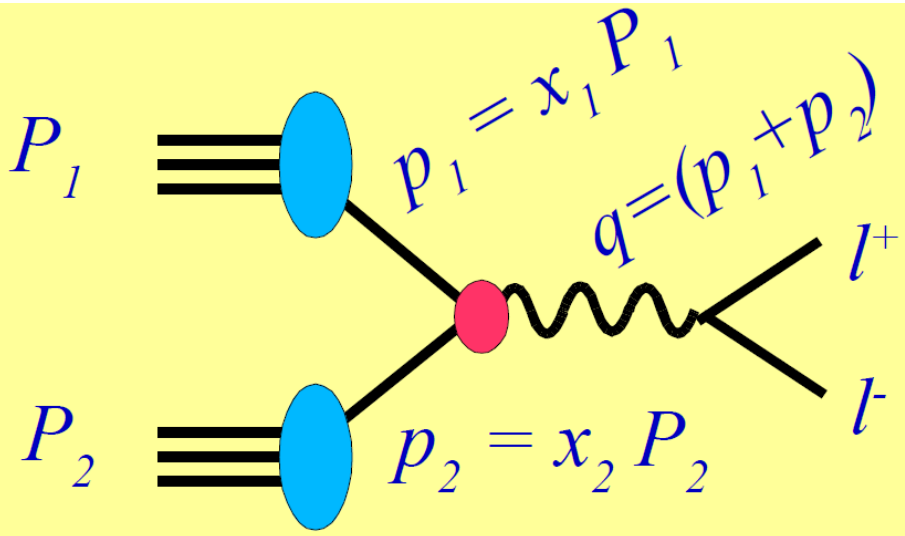
$$\frac{d\hat{\sigma}}{d\cos(\theta)} = Q_i^2 \alpha^2 \frac{\pi}{6} \frac{1}{\hat{s}} \left(1 + \cos^2(\theta)\right)$$

Characteristic of scattering of spin ½ constitutients by a spin 1 vector





U SUSTAVU HADRONA



$$P_1 = \frac{\sqrt{s}}{2}(1,0,0,+1) \qquad P_1^2 = 0$$

$$P_2 = \frac{\sqrt{s}}{2}(1,0,0,-1) \qquad P_2^2 = 0$$

$$\tau = x_1 x_2 = \frac{\hat{s}}{s} \equiv \frac{Q^2}{s}$$

$$s = (P_1 + P_2)^2 = \frac{\hat{s}}{x_1 x_2} = \frac{\hat{s}}{\tau}$$

Fractional energy² between partonic and hadronic system

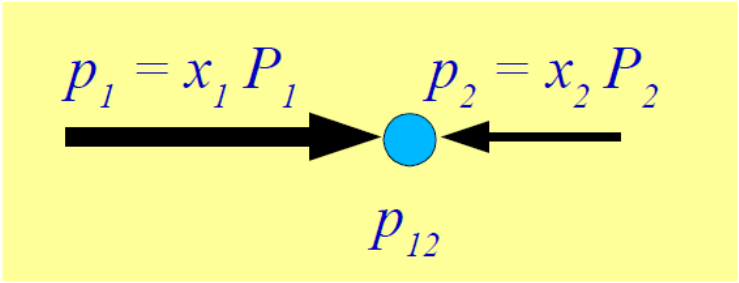
$$\frac{d\sigma}{dQ^2} = \sum_{q,\bar{q}} \int dx_1 \int dx_2 \left\{ q(x_1)\bar{q}(x_2) + \bar{q}(x_1) q(x_2) \right\} \hat{\sigma}_0 \, \delta(Q^2 - \hat{s})$$

Hadronic cross section

Parton distribution functions

Partonic cross section

RASPODJELA LONGITUDINALNOG IMPULSA



$$p_{12} = (p_1 + p_2) = (E_{12}, 0, 0, p_L)$$

$$E_{12} = \frac{\sqrt{s}}{2}(x_1 + x_2)$$

$$p_L = \frac{\sqrt{s}}{2}(x_1 - x_2) \equiv \frac{\sqrt{s}}{2} x_F$$

x_F is a measure of the longitudinal momentum

The rapidity is defined as:

$$x_{1,2} = \sqrt{\tau}\, e^{\pm y}$$

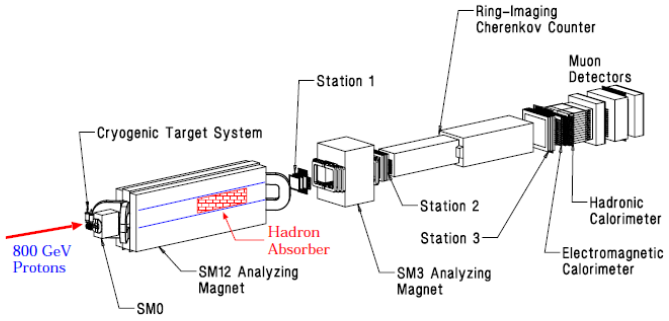
$$y = \frac{1}{2} \ln\left\{\frac{E_{12} + p_L}{E_{12} - p_L}\right\} = \frac{1}{2} \ln\left\{\frac{x_1}{x_2}\right\}$$

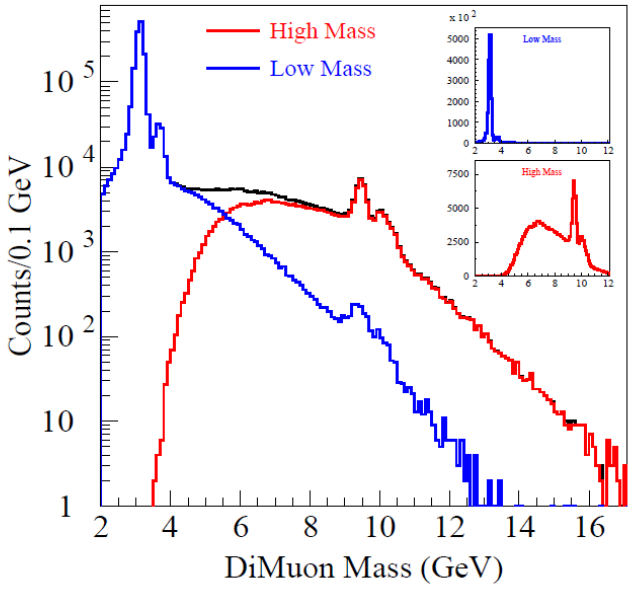
$$dx_1\, dx_2 = d\tau\, dy$$

$$dQ^2\, dx_F = dy\, d\tau\; s\; \sqrt{x_F^2 + 4\tau}$$

$$\frac{d\sigma}{dQ^2\, dx_F} = \frac{4\pi\alpha^2}{9Q^4} \frac{1}{\sqrt{x_F^2 + 4\tau}}\, \tau \sum_{q,\bar{q}} Q_i^2 \left\{q(x_1)\bar{q}(\tau/x_1) + \bar{q}(x_1) q(\tau/x_1)\right\}$$

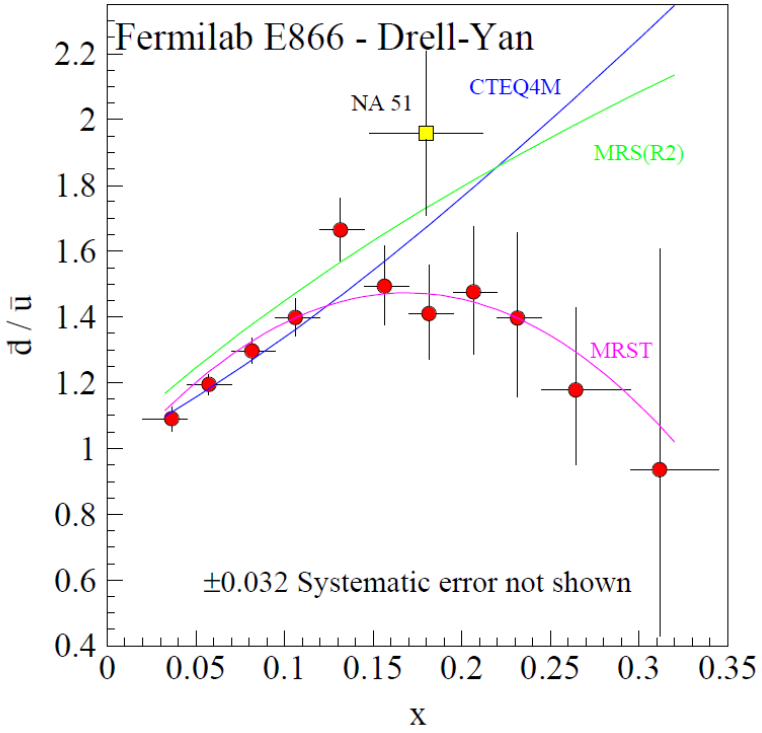
MJERENJE ASIMETRIJE ANTIKVARKOVA MORA





ACU, ANL, FNAL, GSU, IIT, LANL, LSU,
NMSU, UNM, ORNL, TAMU, Valpo.

800 GeV $p + p$ and $p + d \rightarrow \mu^+\mu^- X$



POMOĆU IZOSPINSKE SIMETRIJE

In the limit $x_1 >> x_2$:

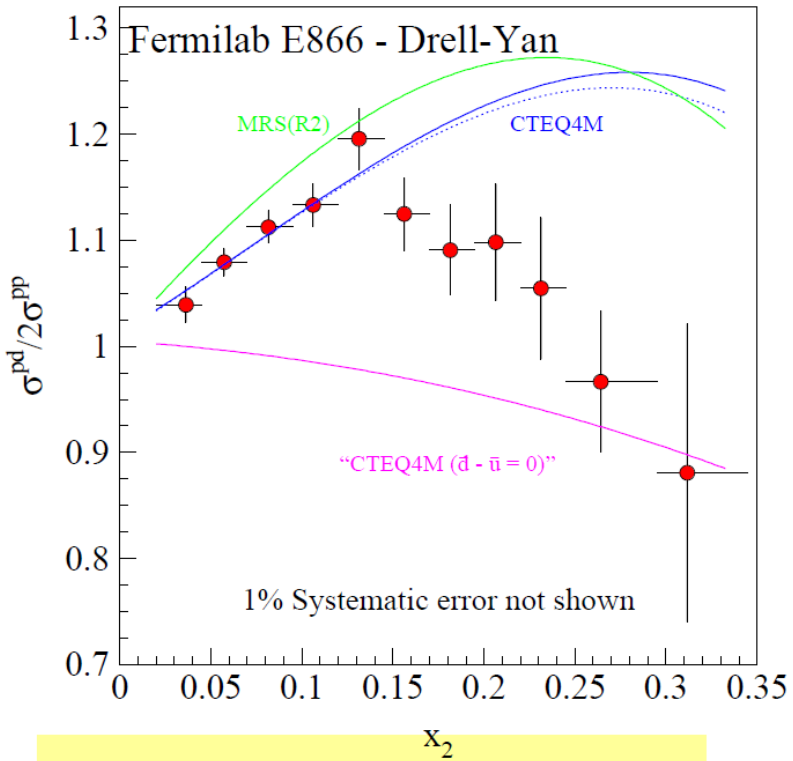
$$\sigma^{pp} \propto \frac{4}{9} u(x_1)\bar{u}(x_2) + \frac{1}{9} d(x_1)\bar{d}(x_2)$$

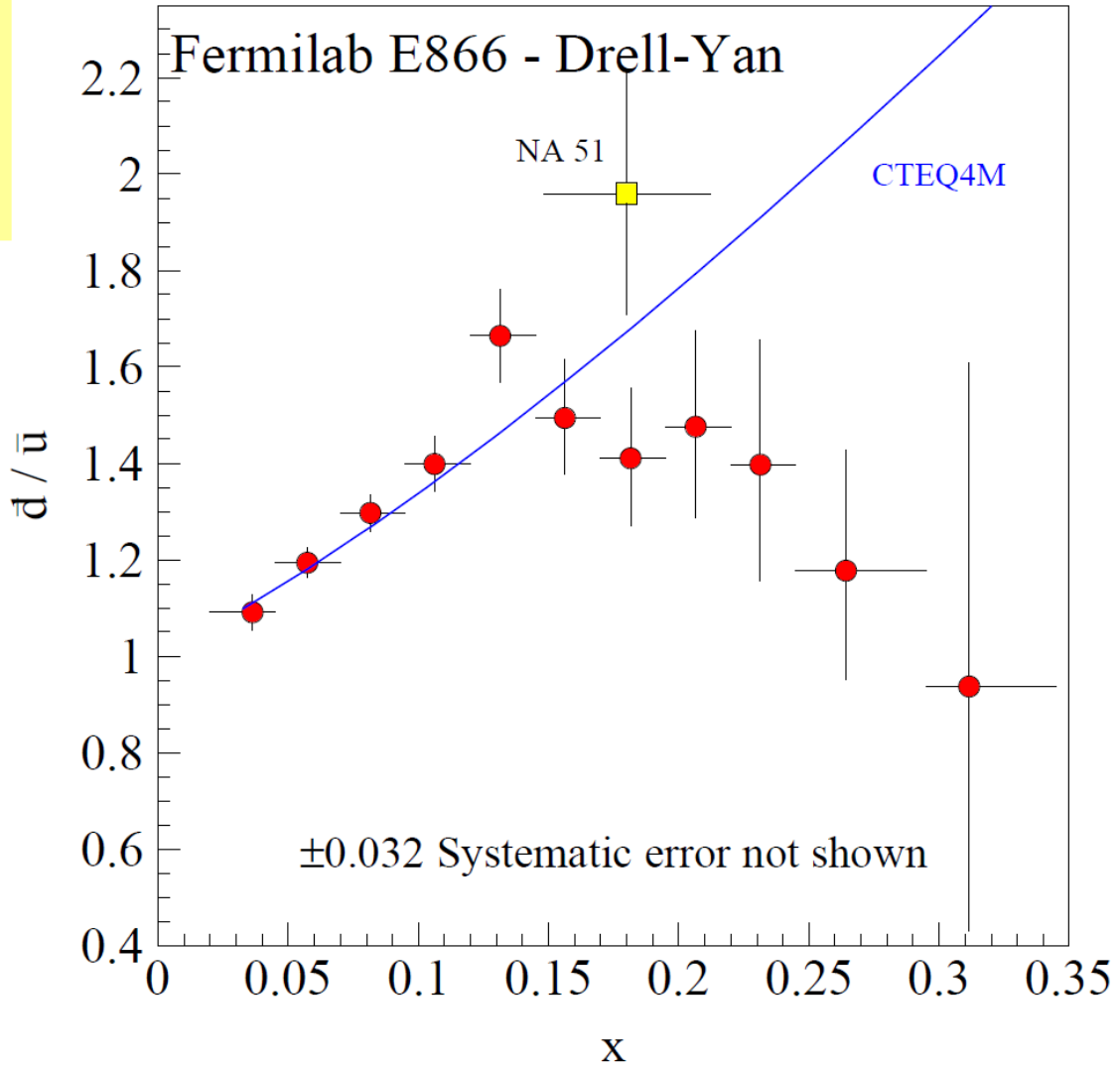
$$\sigma^{pn} \propto \frac{4}{9} u(x_1)\bar{d}(x_2) + \frac{1}{9} d(x_1)\bar{u}(x_2)$$

For the ratio we have:

$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2} \frac{\left(1 + \frac{1}{4}\frac{d_1}{u_1}\right)}{\left(1 + \frac{1}{4}\frac{d_1}{u_1}\frac{\bar{d}_2}{\bar{u}_2}\right)} \left(1 + \frac{\bar{d}_2}{\bar{u}_2}\right) \approx \frac{1}{2}\left(1 + \frac{\bar{d}_2}{\bar{u}_2}\right)$$

$$\frac{\sigma^{pd}}{2\,\sigma^{pp}} \approx \frac{1}{2}\left(1+\frac{\bar{d}_2}{\bar{u}_2}\right)$$





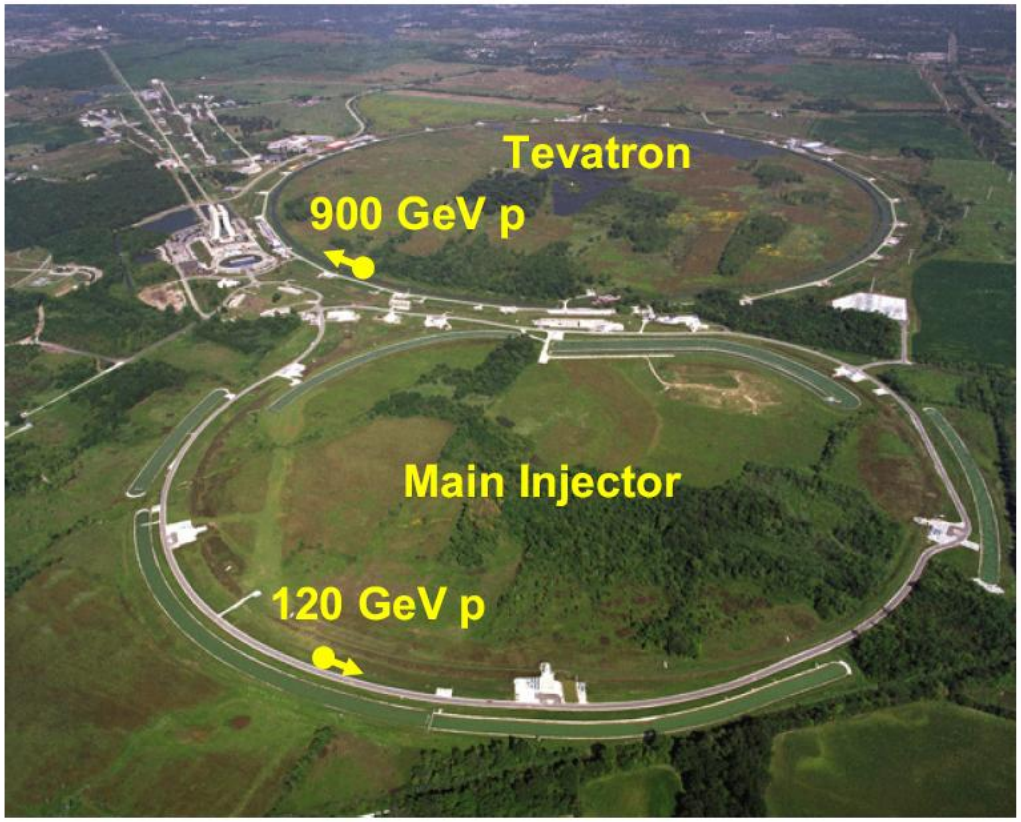
Implies R<1 for large x:

$$\bar{d} \ll \bar{u}$$

E.A. Hawker, et al. [FNAL E866/NuSea Collaboration], Measurement of the light antiquark flavor asymmetry in the nucleon sea, PRL 80, 3715 (1998)

SUDARI PROTONA i ANTIPROTONA NA TEVATRONU

★ $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV



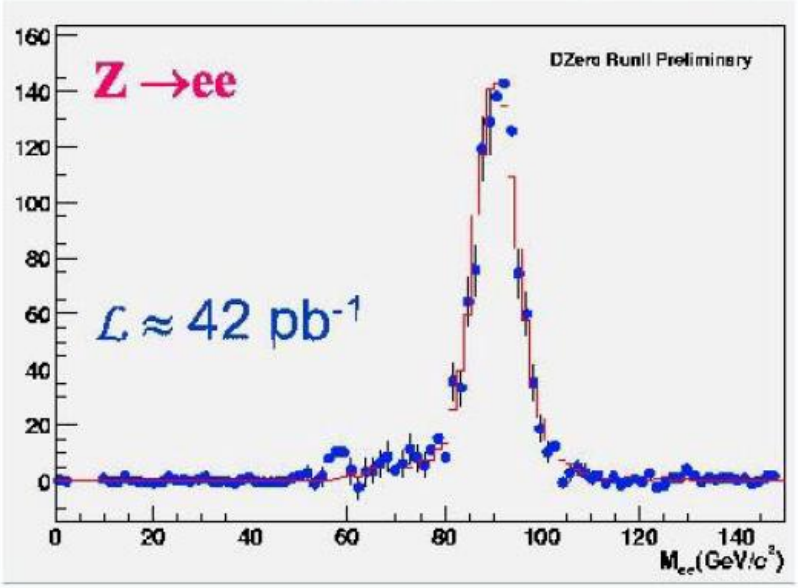
Two main accelerators:

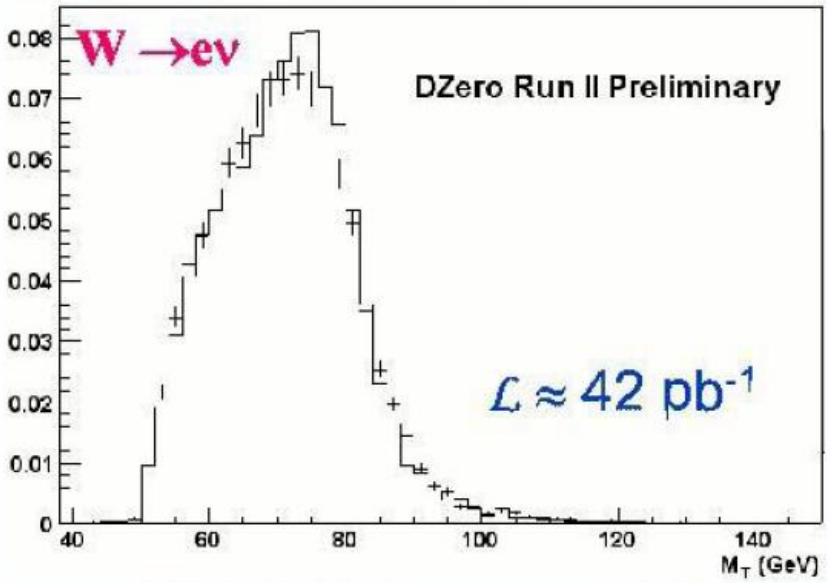
★ **Main Injector**

- Accelerates 8 GeV p to 120 GeV
- also $\bar{p}$ to 120 GeV
- Protons sent to Tevatron & MINOS
- $\bar{p}$ all go to Tevatron

★ **Tevatron**

- 4 mile circumference
- accelerates $p/\bar{p}$ from 120 GeV to 900 GeV





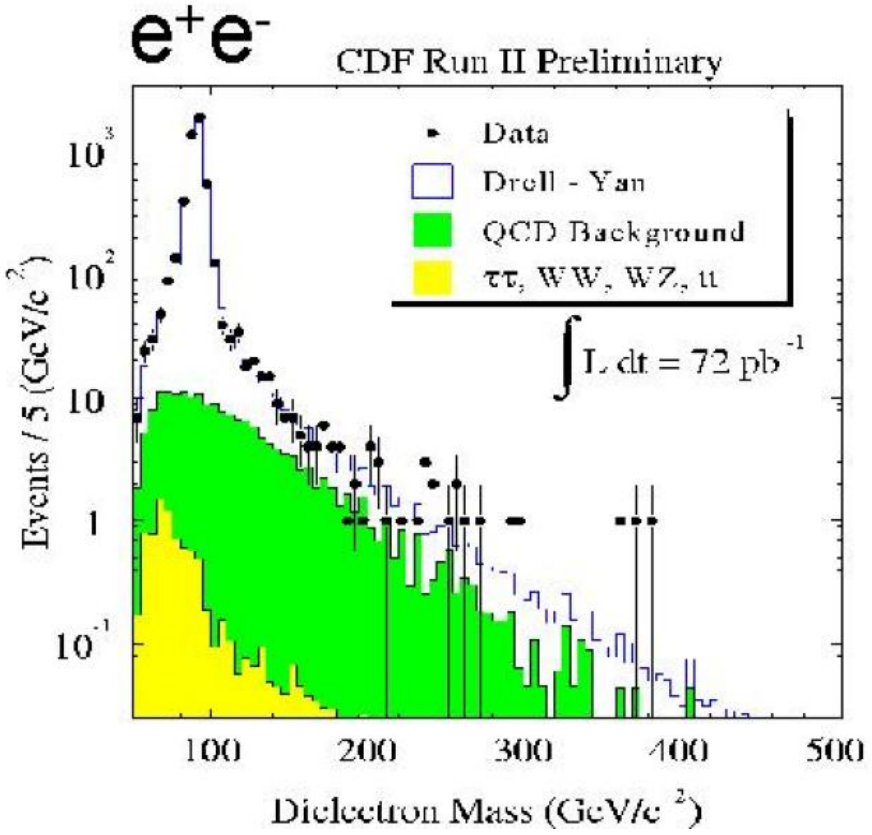
- 1139 Z→ee candidates
  - $|\eta^e|<1.1$, $E_T>25$ GeV, no track match required
- $\varepsilon(Z)\approx 8\%$, bkgd ~ 18%

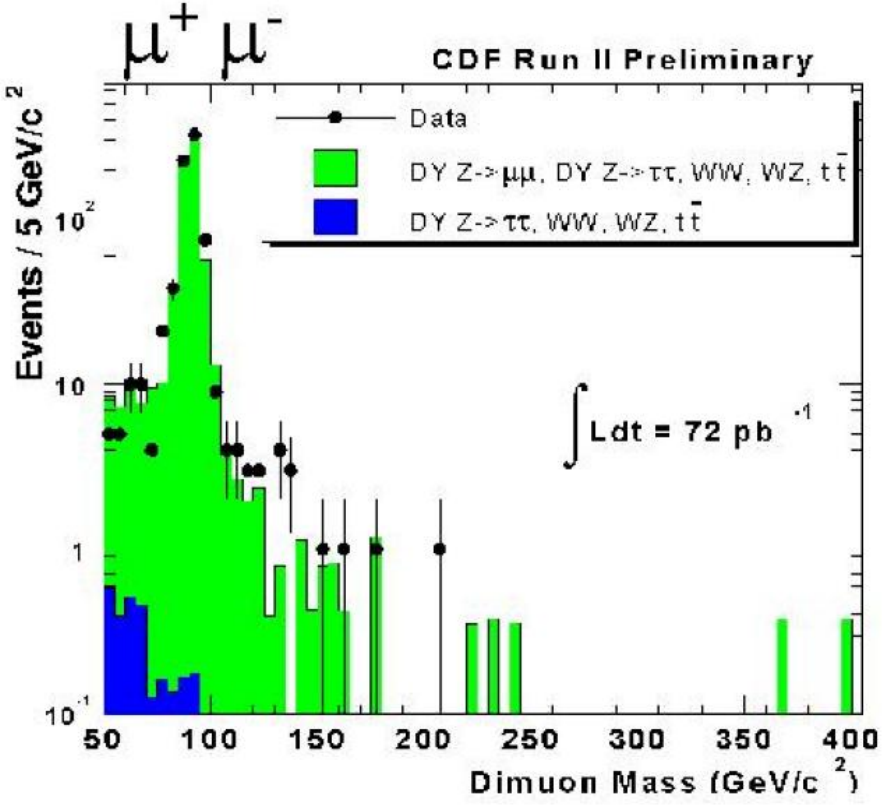
- 27370 W→eν candidates
  - $|\eta^e|<1.1$, E_T & $\not\!\!E_T>25$ GeV
- $\varepsilon(W)\approx 16\%$
- bkgd ~ 3% QCD, ~1.5% τ

$$\sigma(W)Br(W \to e\nu) = 3054 \pm 100(N_W) \pm 86(sys) \pm 305(lumi) \quad pb$$

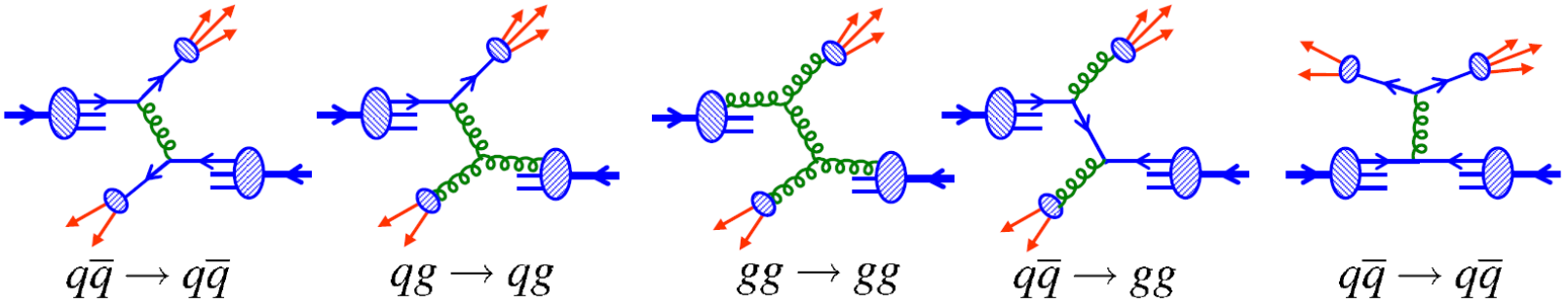
$$\sigma(Z)Br(Z \to ee) = 294 \pm 11(N_Z) \pm 8(sys) \pm 29(lumi) \quad pb$$

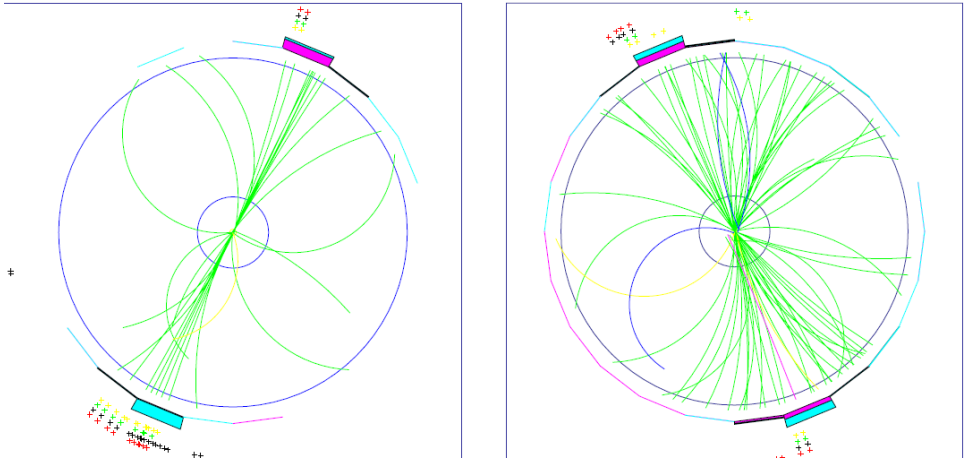
DRELL-YAN-ove PRODUKCIJE na TEVATRON-u

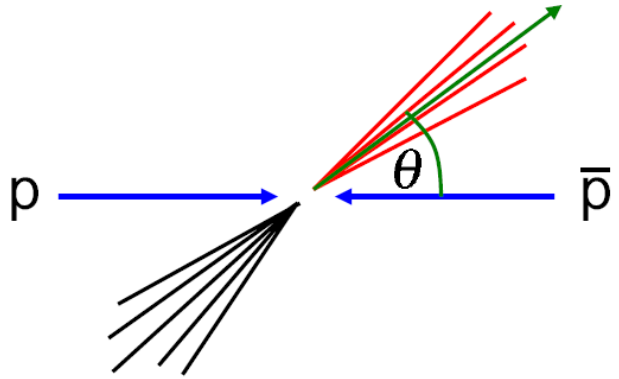




PROIZVODNJA HADRONSKIH MLAZOVA



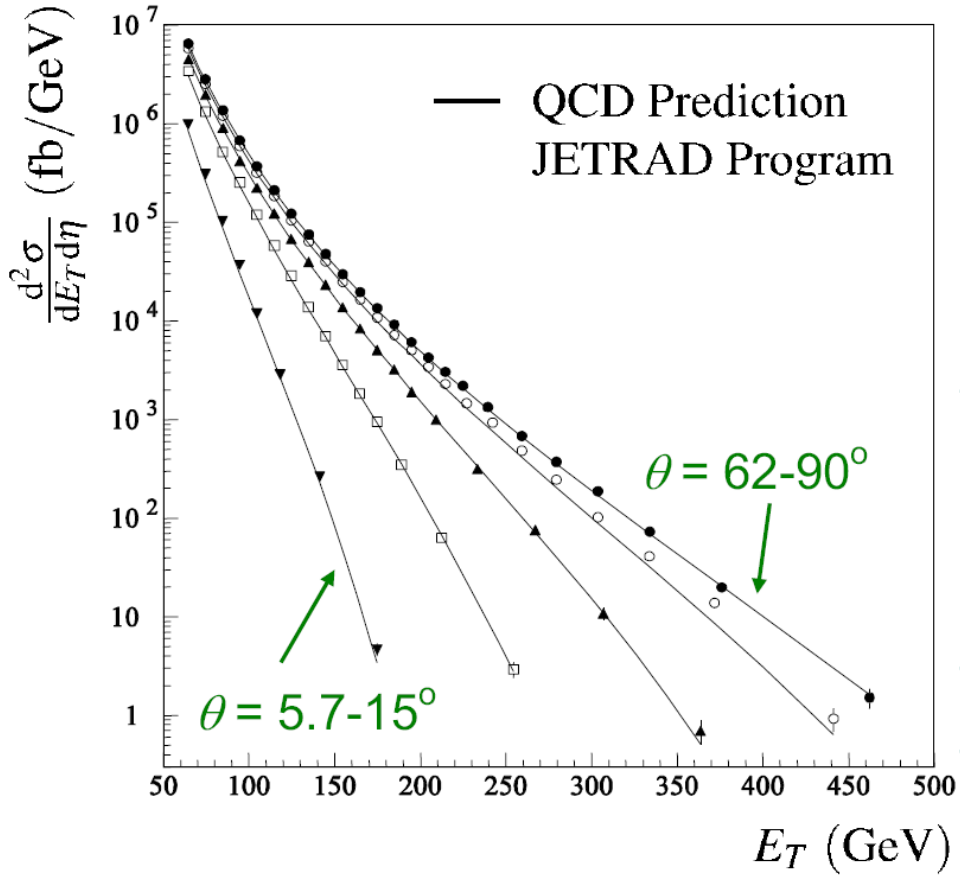




★ **Measure cross-section in terms of**

- **"transverse energy"** $E_T = E_{\text{jet}} \sin\theta$
- **"pseudorapidity"** $\eta = \ln\left[\cot\left(\frac{\theta}{2}\right)\right]$

…don't worry too much about the details here, what matters is that…



D0 Collaboration, Phys. Rev. Lett. 86 (2001)

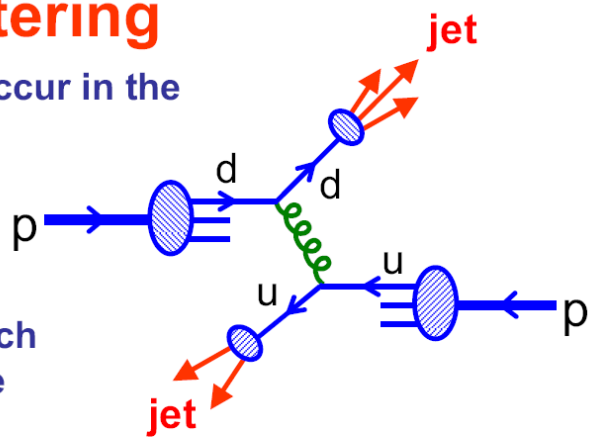
★**QCD predictions provide an excellent description of the data**

★**NOTE:**

- **at low E_T cross-section is dominated by low x partons**
  i.e. gluon-gluon scattering
- **at high E_T cross-section is dominated by high x partons**
  i.e. quark-antiquark scattering

SUDARI PROTONA i PROTONA NA LHC-u

Quark-Quark Scattering



- Consider the process $u + d \rightarrow u + d$ which can occur in the high energy proton-proton scattering
- There are nine possible colour configurations of the colliding quarks which are all equally likely.
- Need to determine the average matrix element which is the sum over all possible colours divided by the number of possible initial colour states

$$\langle |M_{fi}|^2 \rangle = \frac{1}{3} \cdot \frac{1}{3} \sum_{i,j,k,l=1}^{3} |M_{fi}(ij \rightarrow kl)|^2$$

- The colour average matrix element contains the average colour factor

$$\langle |C|^2 \rangle = \frac{1}{9} \sum_{i,j,k,l=1}^{3} |C(ij \rightarrow kl)|^2$$

- For $qq \rightarrow qq$

rr→rr,.. *rb→rb,..* *rb→br,..*

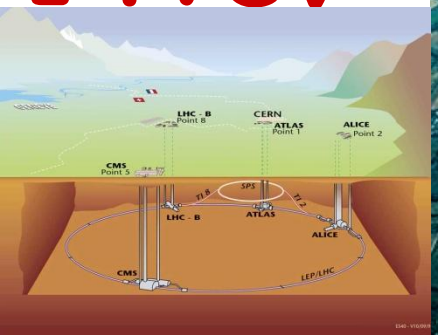
$$\langle |C|^2 \rangle = \frac{1}{9} \left[3 \times \left(\frac{1}{3} \right)^2 + 6 \times \left(-\frac{1}{6} \right)^2 + 6 \times \left(\frac{1}{2} \right)^2 \right] = \frac{2}{9}$$

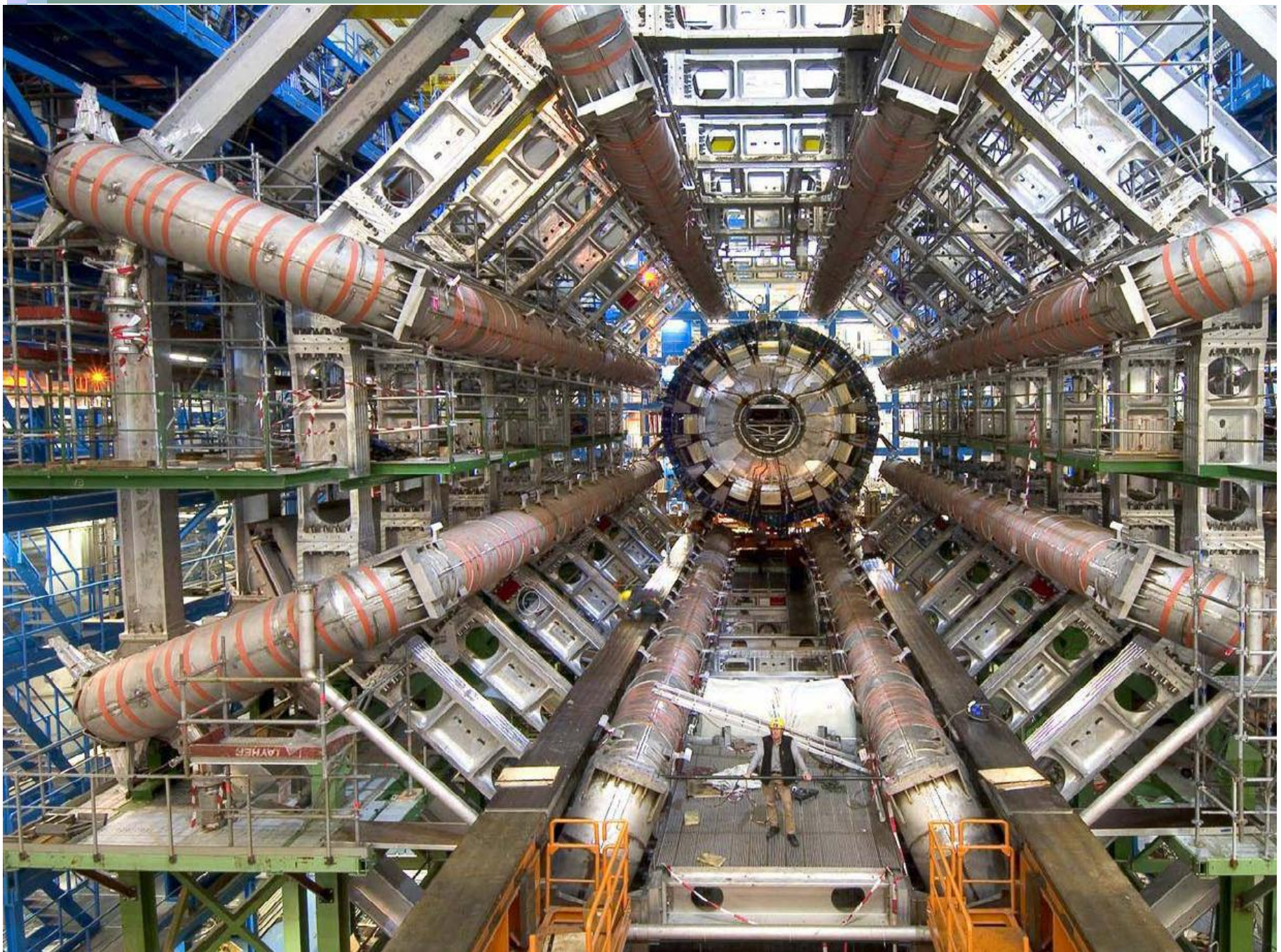
LHC

supra-
vodljivi
magneti

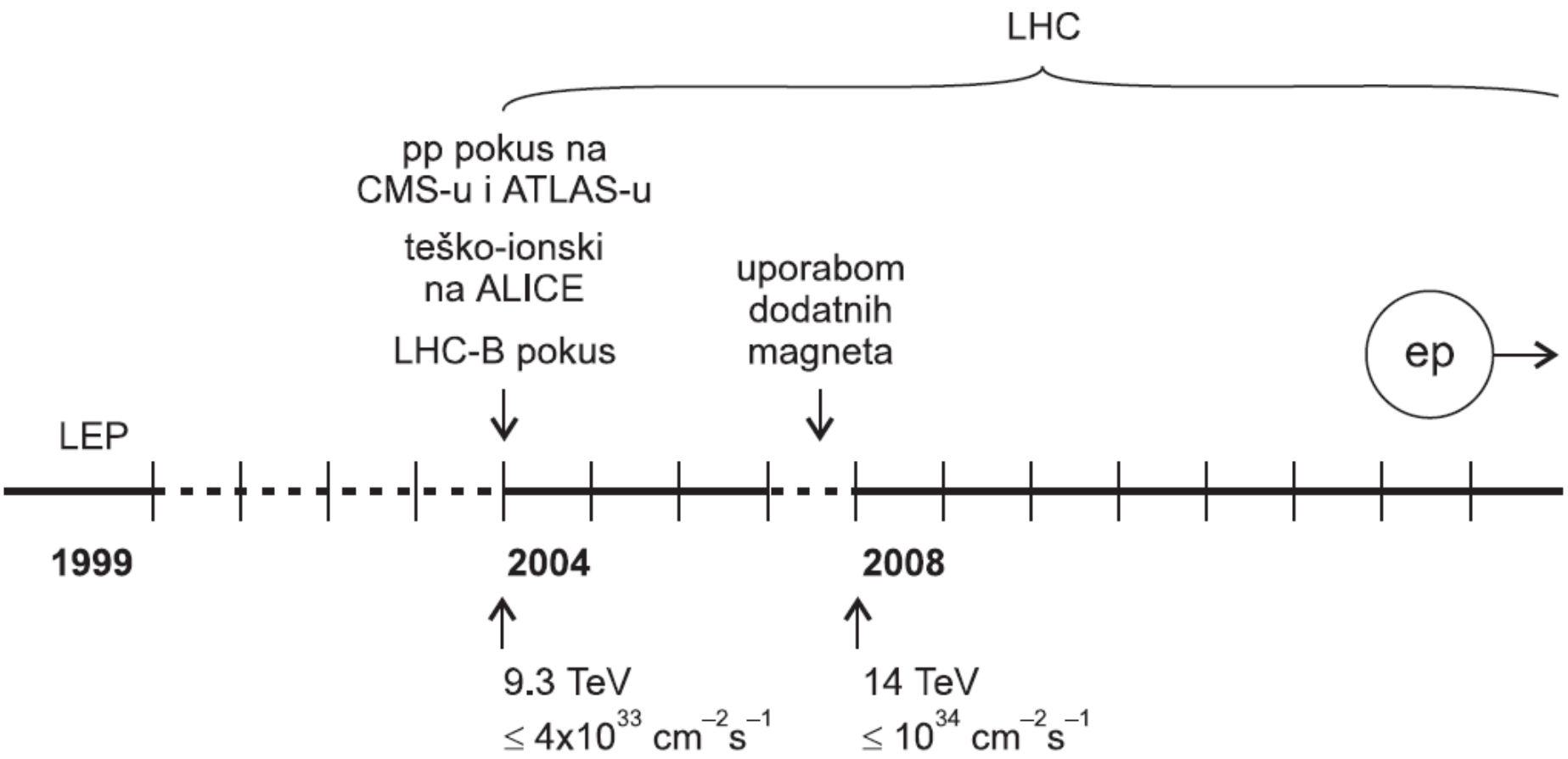
opsega
27 km

energ.
Ecm
14TeV



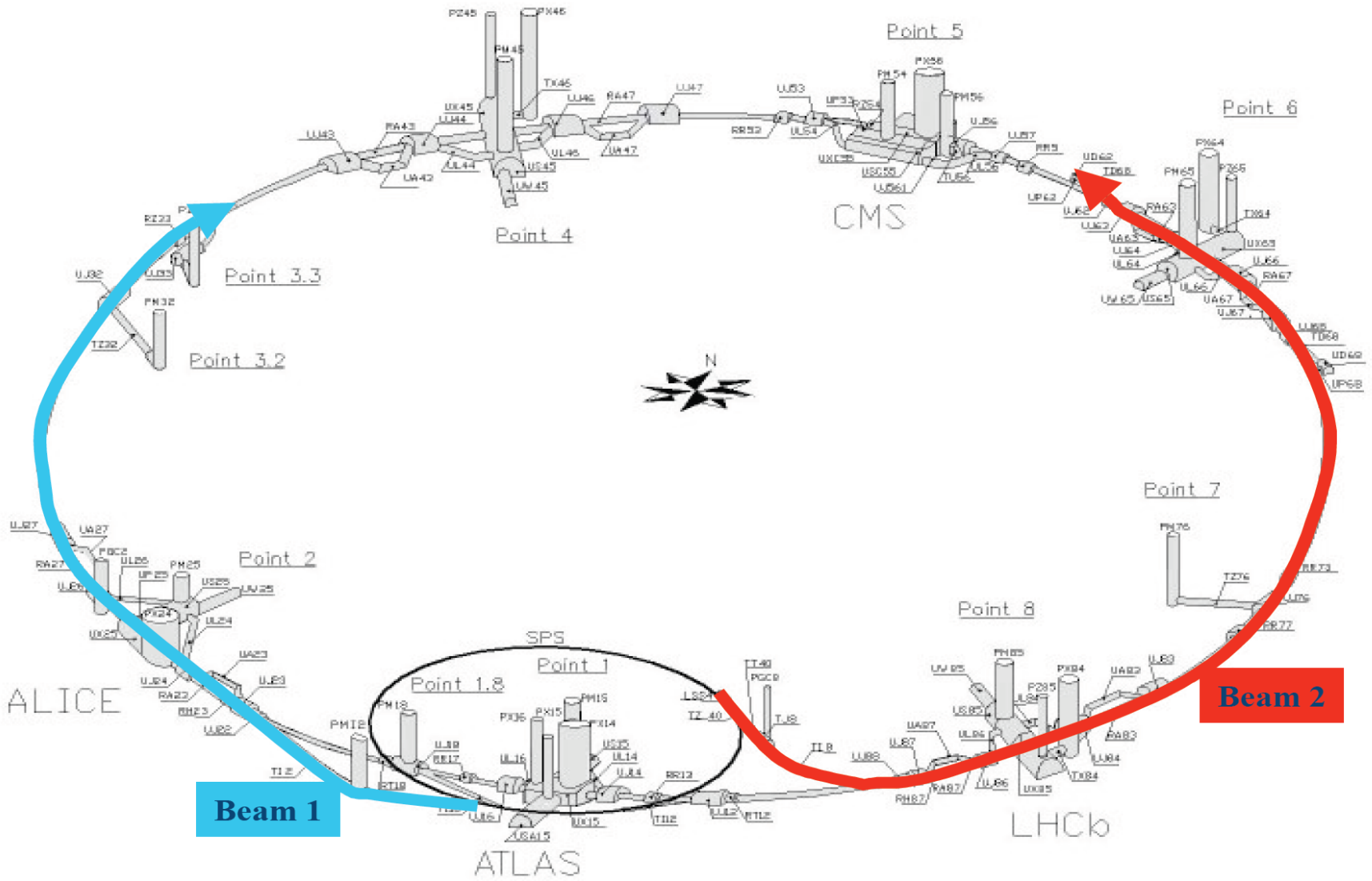


Higgsov bozon je sudbinski vezan uz supravodljivost (supravodljive magnete LHC-a)



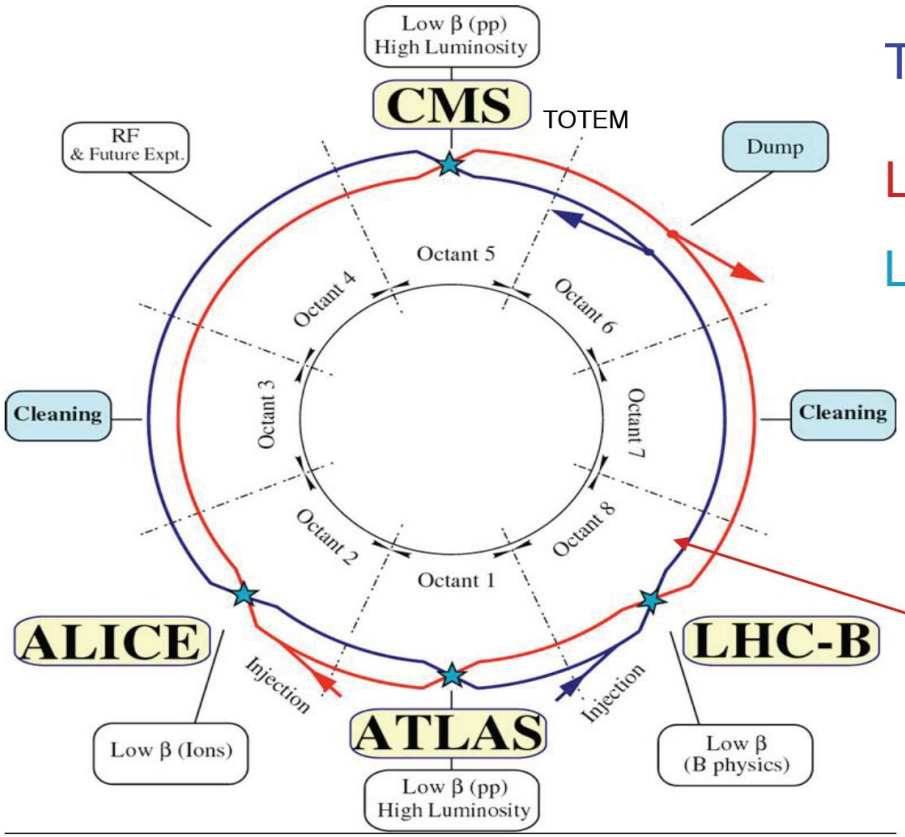
Slika 1.16: *Kalendar **LHC** projekta*

Injektiranje 1.snopa 10.9.2008



Podaci o LHC-u

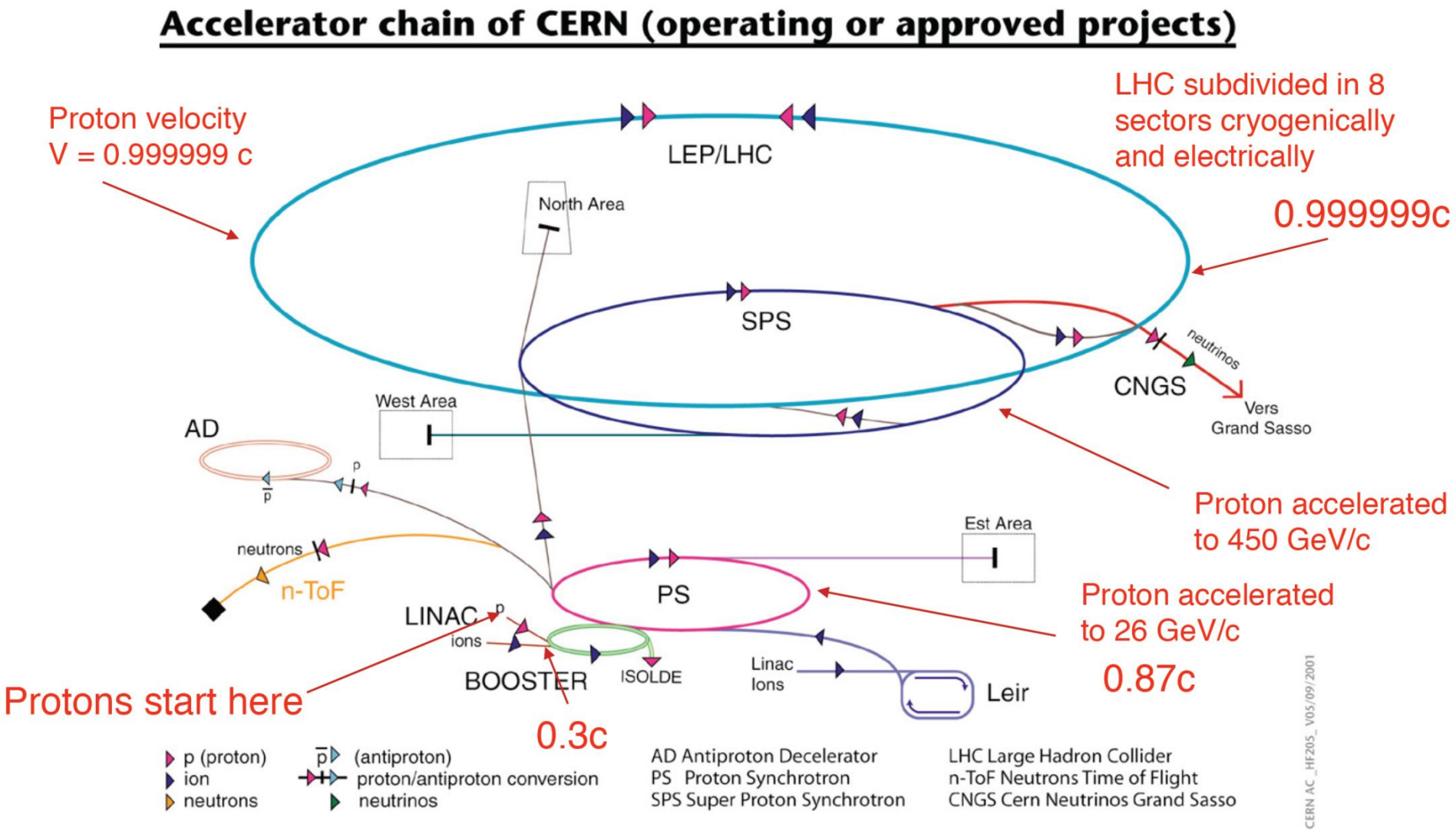
~ 65% of the 27 km long circumference covered with 1232 2-in-1 superconducting dipoles of 14.3m length operated at 1.9 ^{o}K giving a field of B = 8.3T , 500 2-in-1 quadrupoles with 215T/m, altogether 1200 tons of superconducting cable and 40.000 tons of material at 1.9 ^{o}K superfluid He temperature!.



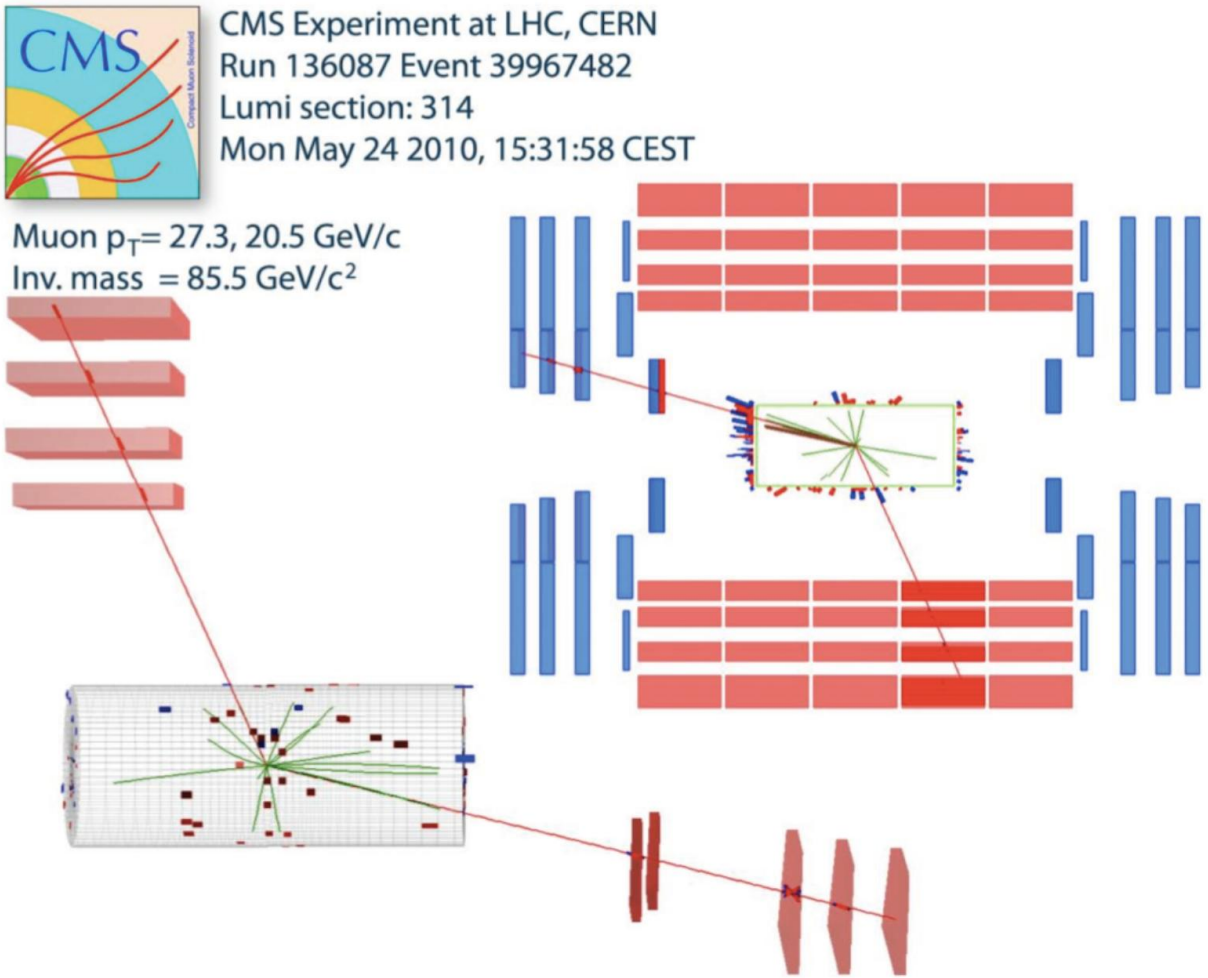
Tevatron	p-p	2.000 GeV	$3*10^{32}$ cm^{-2} s^{-1}
LHC	pp	14.000 GeV	10^{34} cm^{-2} s^{-1}
LHC	pp	7.000 GeV	~10^{32} cm^{-2} s^{-1}
in 2010/2011		→	~10^{33} cm^{-2} s^{-1}

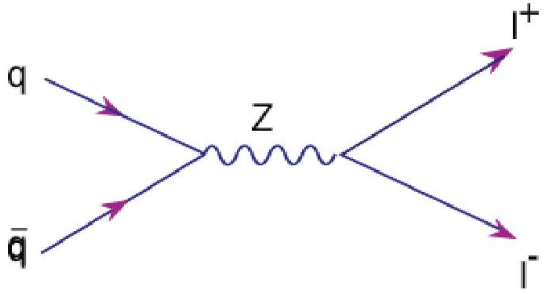
p = ReB

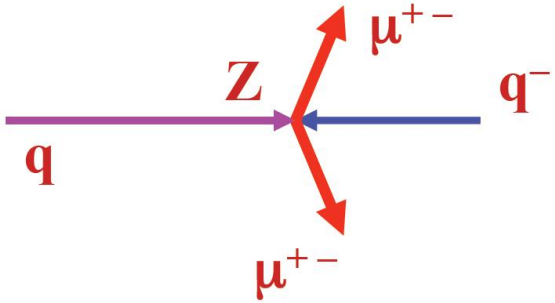
Lanac LHC-ovih injektora



Prvi događaj Z-> mu+ mu- na CMS-u u travnju 2010

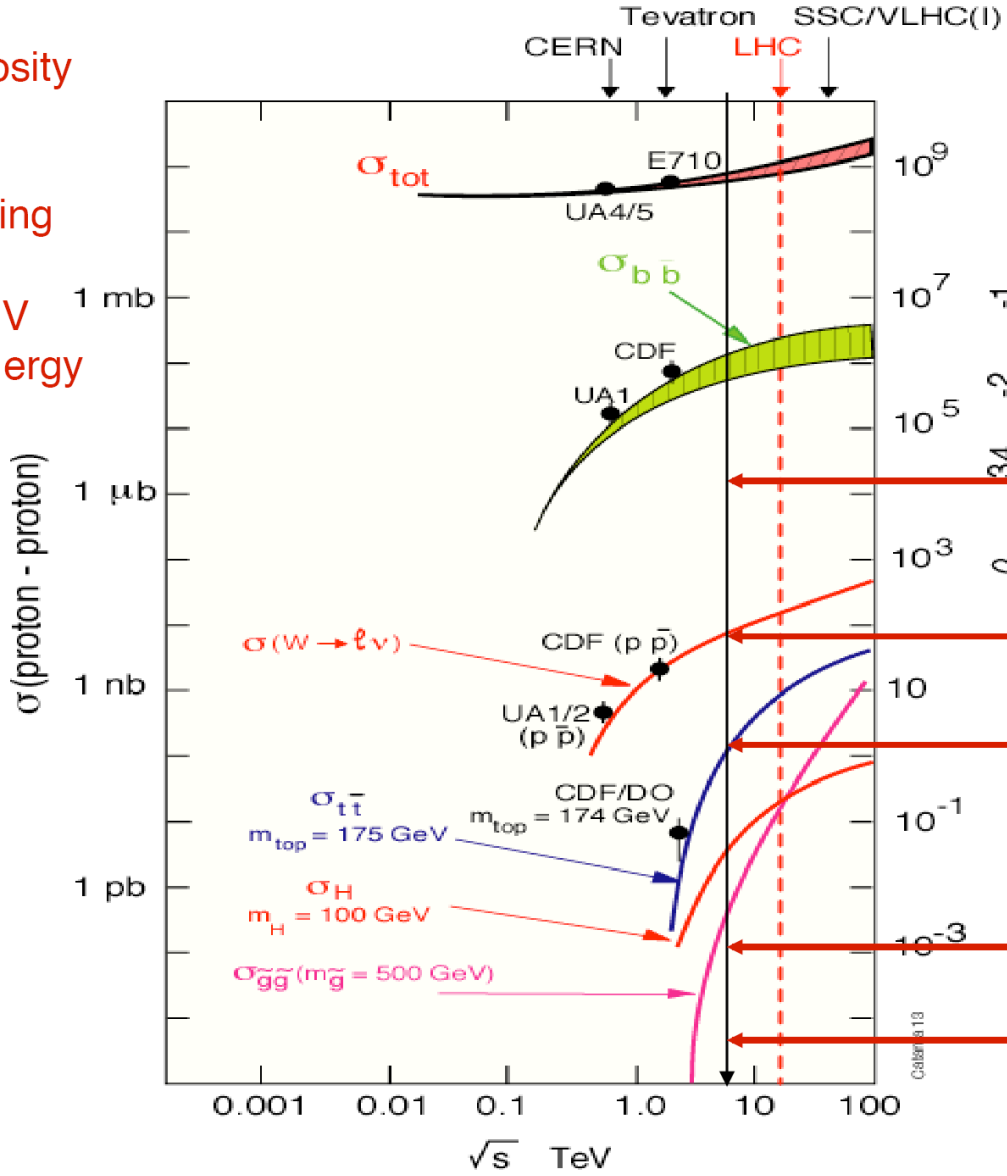






Cross sections and event rates at hadron colliders, opening of channels with increasing luminosity

Increase in luminosity and consequent increase in LHC physics reach during the running in 2010/2011 at 7 TeV center of mass energy



Levels of sensitivity attained taking into account decay branching ratios);

Initial running, hadronic resonances

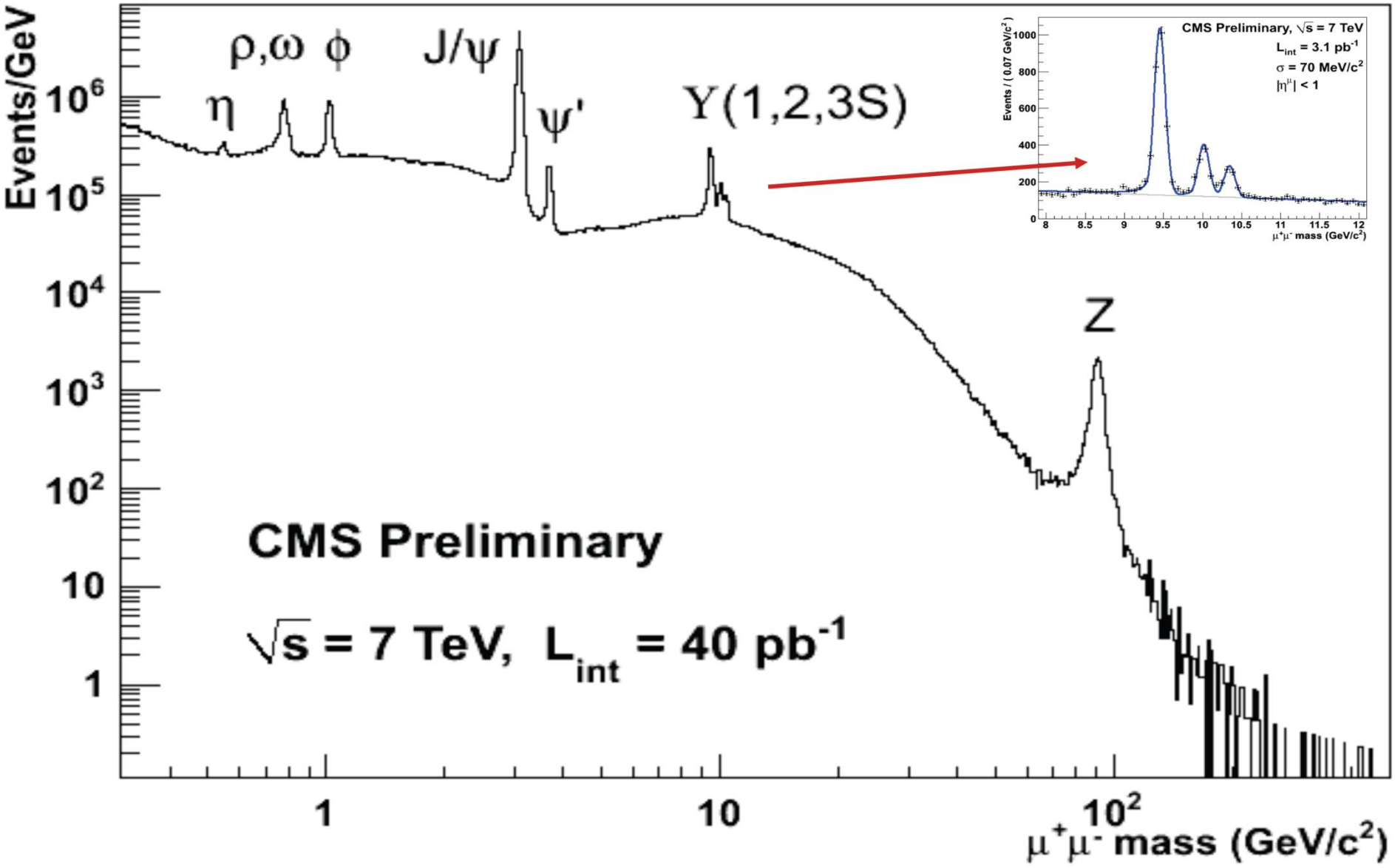
In April 2010, first W,Z events

In July 2010, first tt events

Expected level at end of 2011….

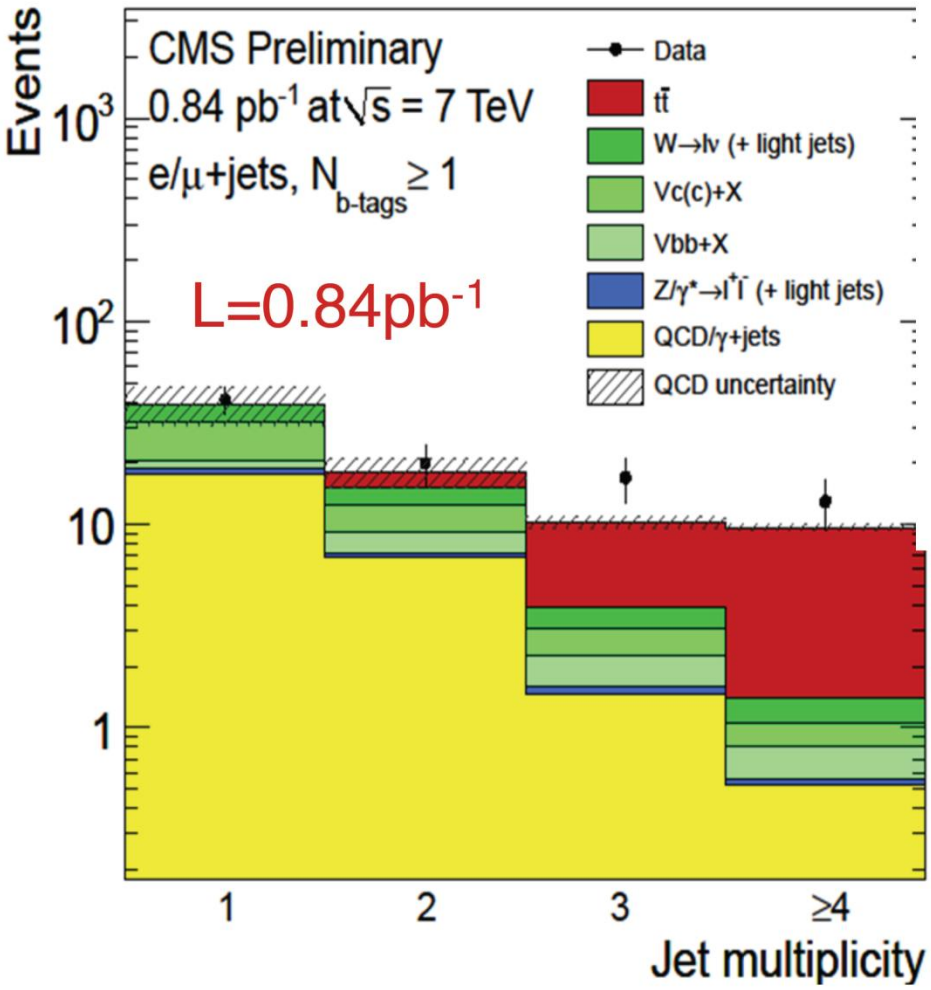
LHC running in 2010/11 at 7 TeV center of mass energy

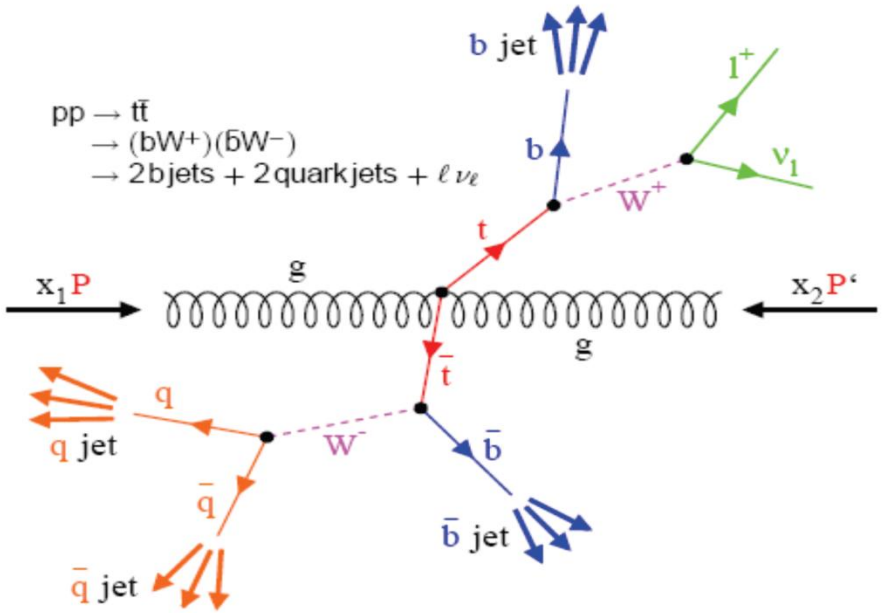
Spektar dimiona na CMS-u 2010



Evidence for top in CMS from Lepton + jets final states, Sept. 2010 with ~1pb^{-1}

e/μ + jets final states

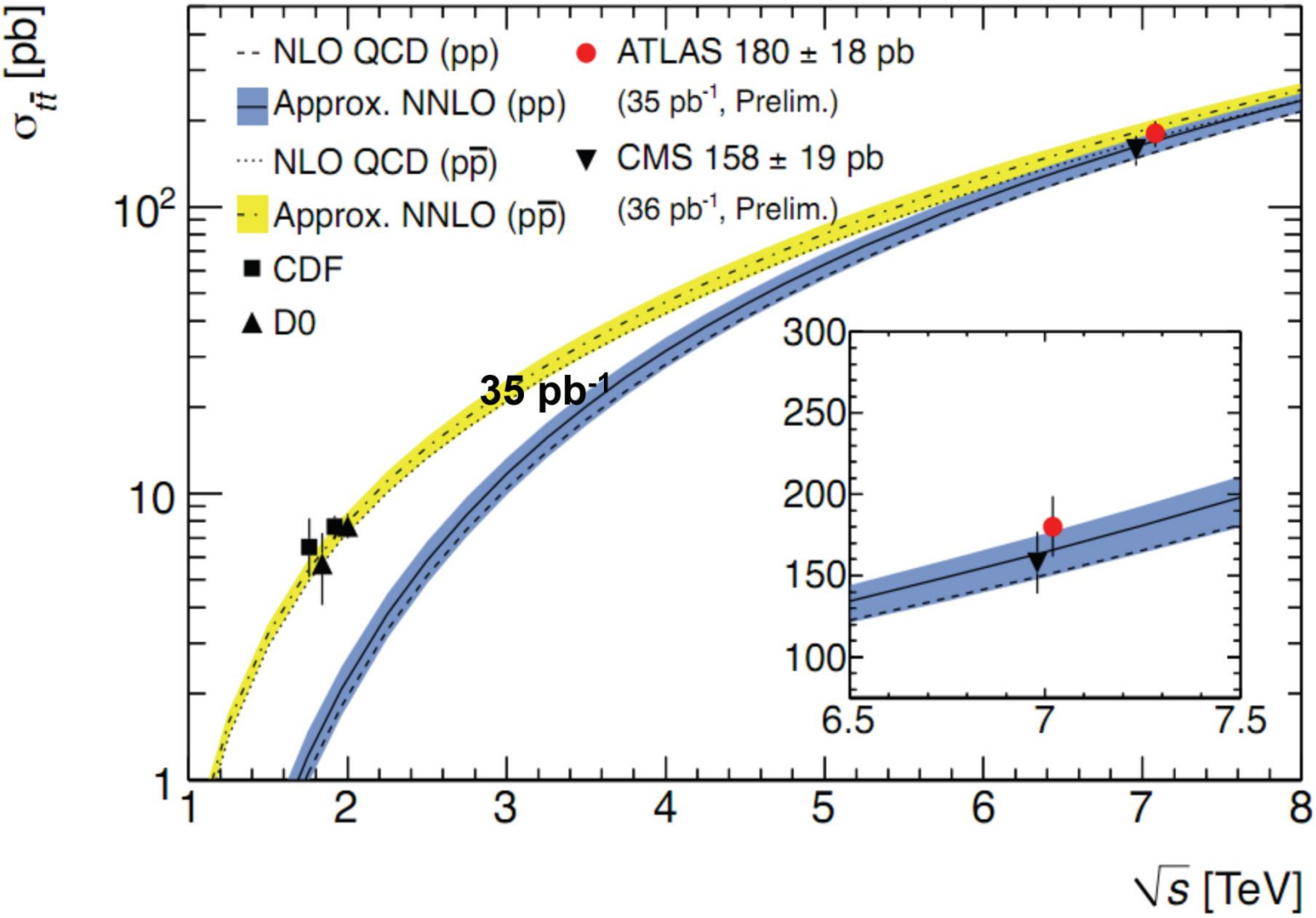




tt → bWbW → blvbqq

For N(jets) ≥3 we count 30 signal candidates over a predicted background of 5.3 events

Top cross section, from Tevatron to LHC with 35 pb^{-1}



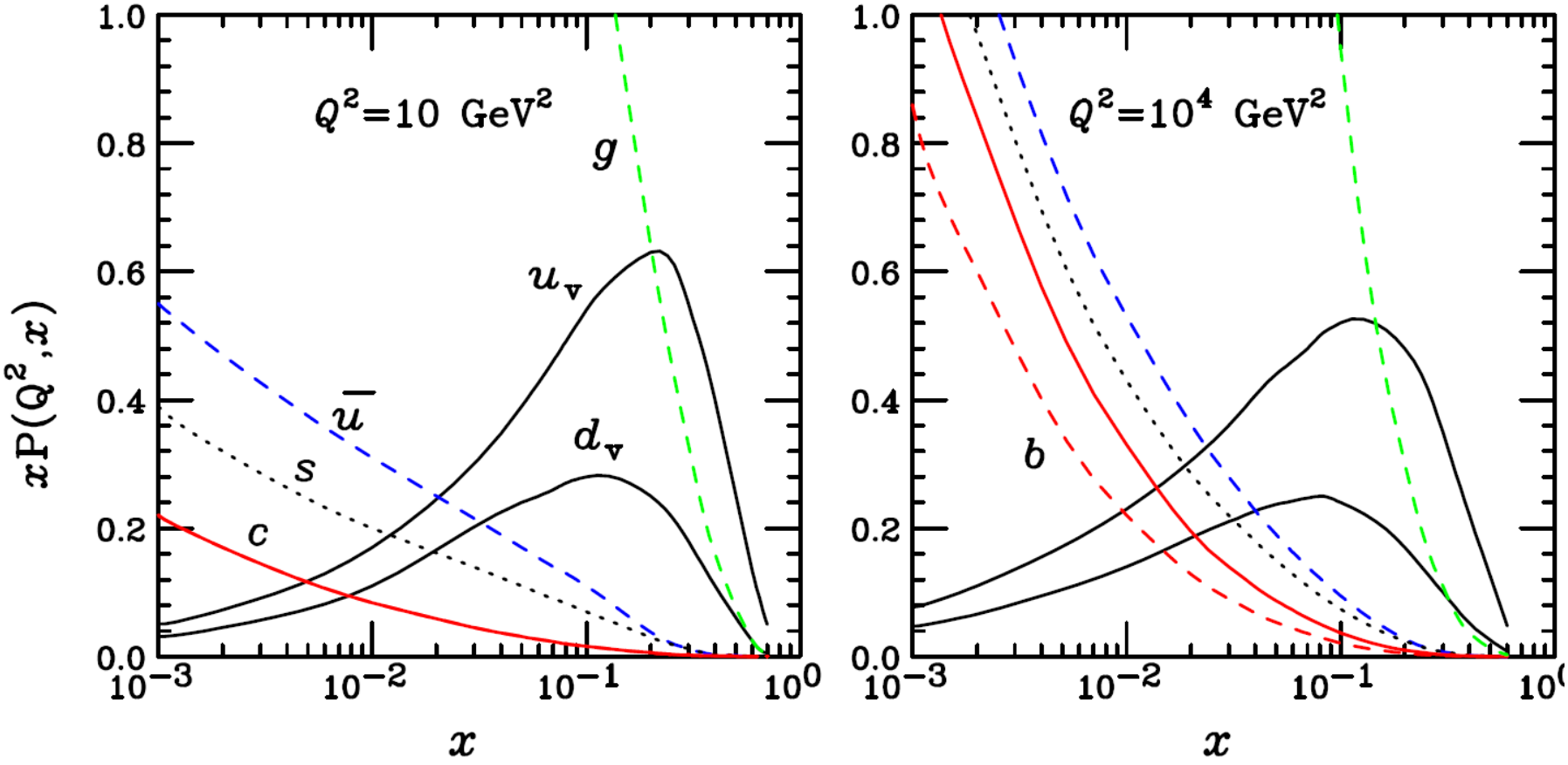
σ(tt) = 180 ± 9± 15 ± 6 pb (10% total uncertainty), ATLAS

Faktorizacija hadronskog procesa velikog prijenosa impulsa na tvrdo partonsko raspršenje konvoluirano PDF-ovima

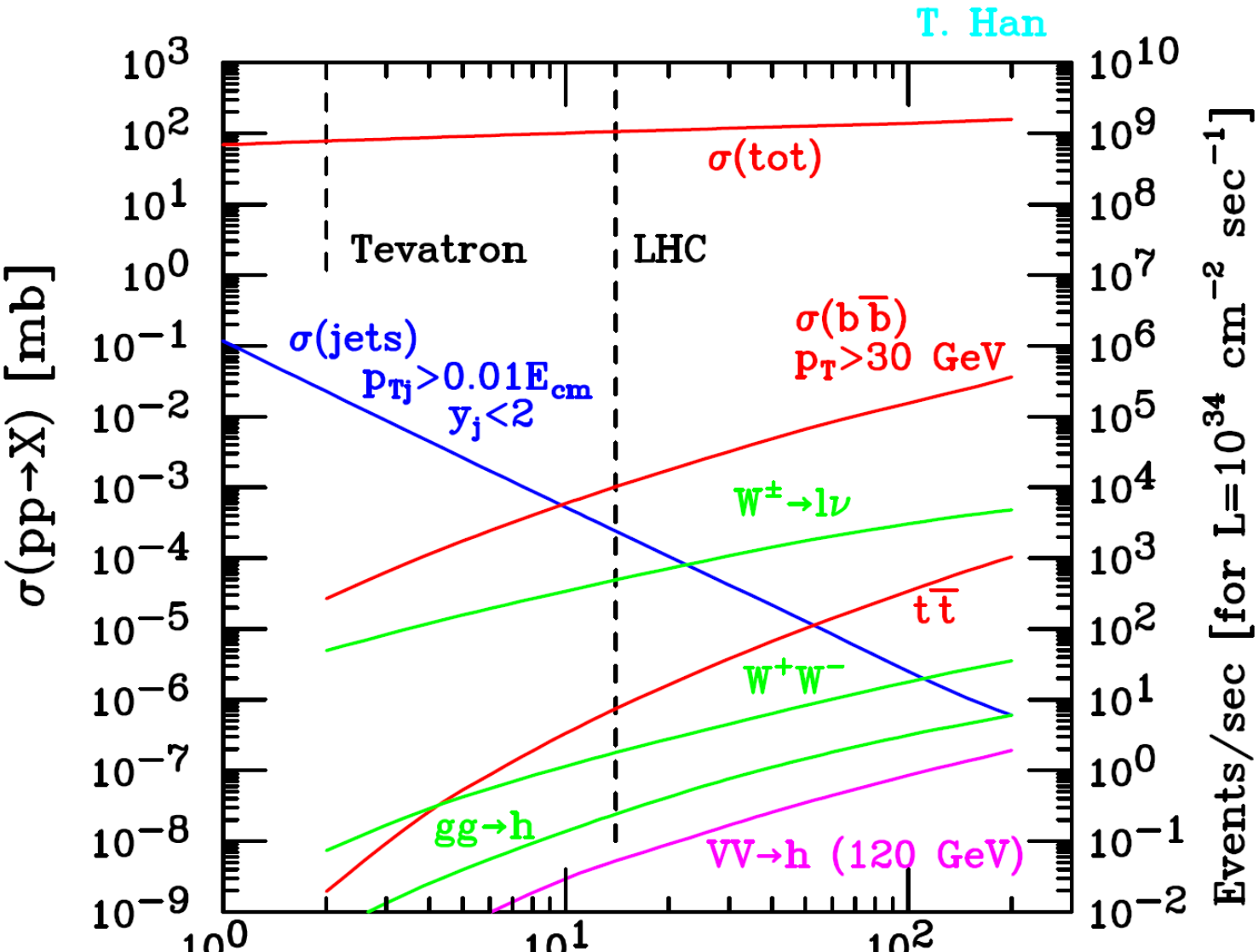
$$\sigma(AB \to F\ X) =$$

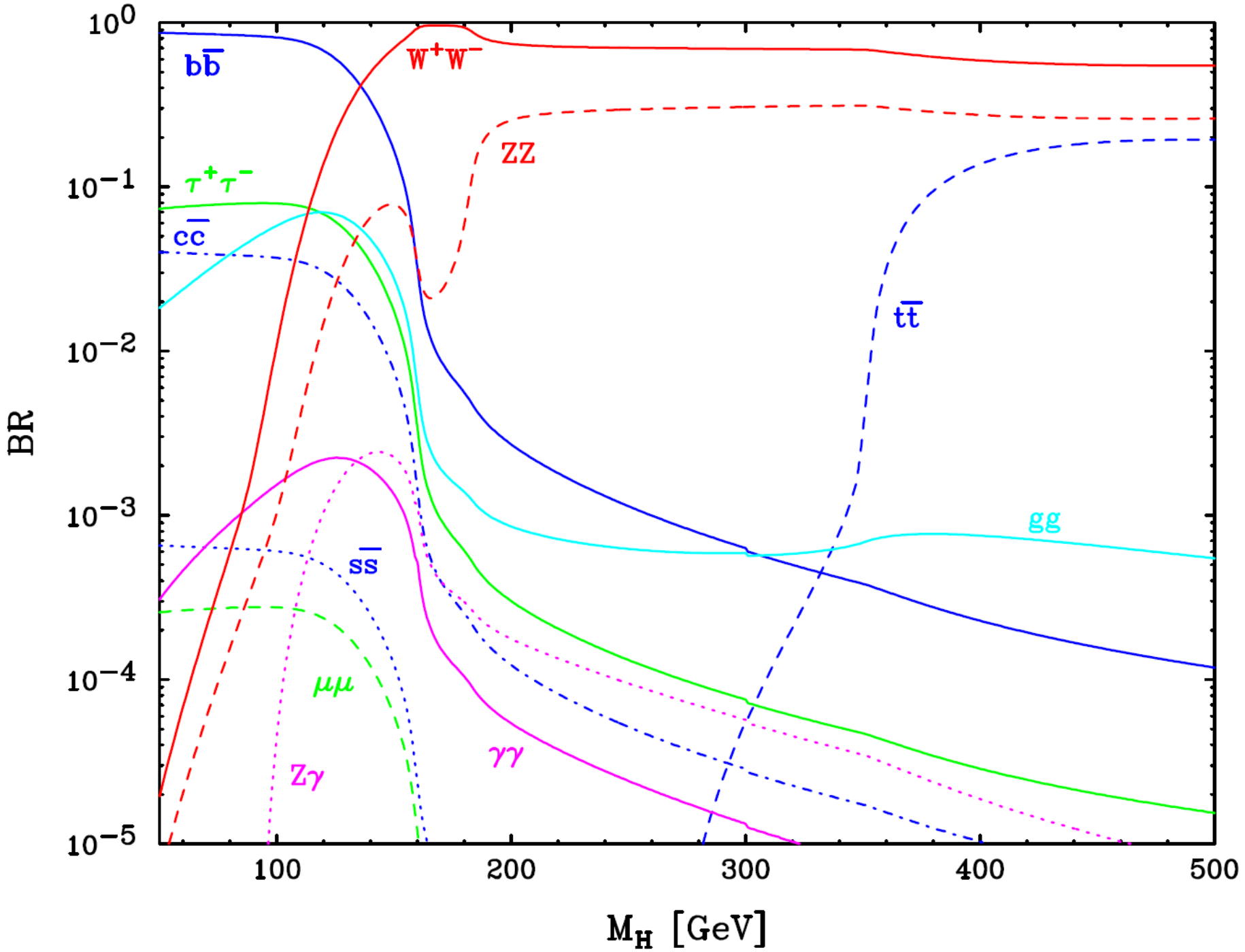
$$\sum_{a,b} \int dx_1 dx_2\ P_{a/A}(x_1, Q^2) P_{b/B}(x_2, Q^2)\ \hat{\sigma}(ab \to F)$$

PDF-ovi CTEQ-5 za dvije različite faktorizacijske skale



PROCESI SM-a za higgs 120 GeV




BR
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
100
200
300
400
500
M_H [GeV]
$b\bar{b}$
W^+W^-
ZZ
$\tau^+\tau^-$
$c\bar{c}$
$t\bar{t}$
gg
$s\bar{s}$
$\mu\mu$
$Z\gamma$
$\gamma\gamma$

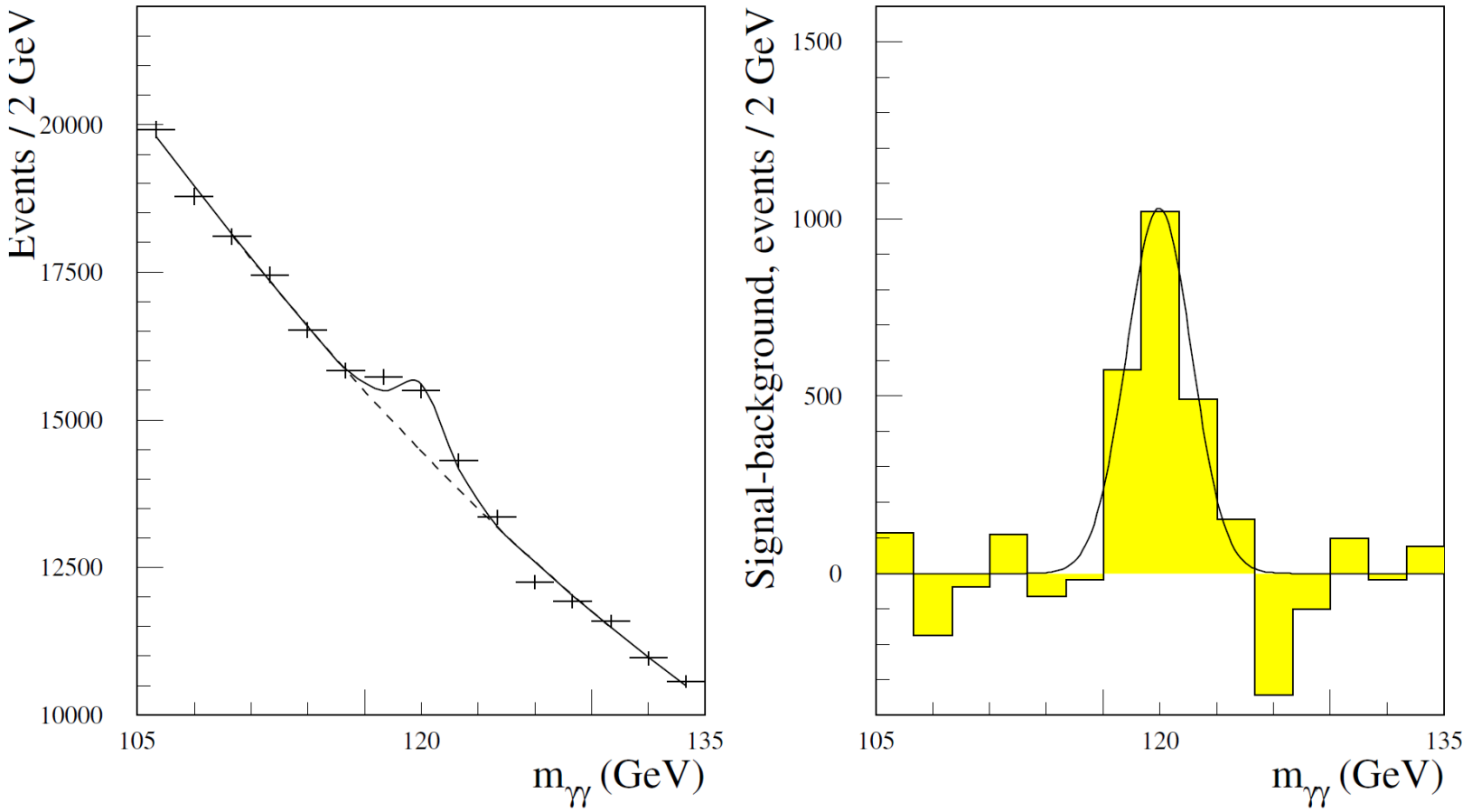
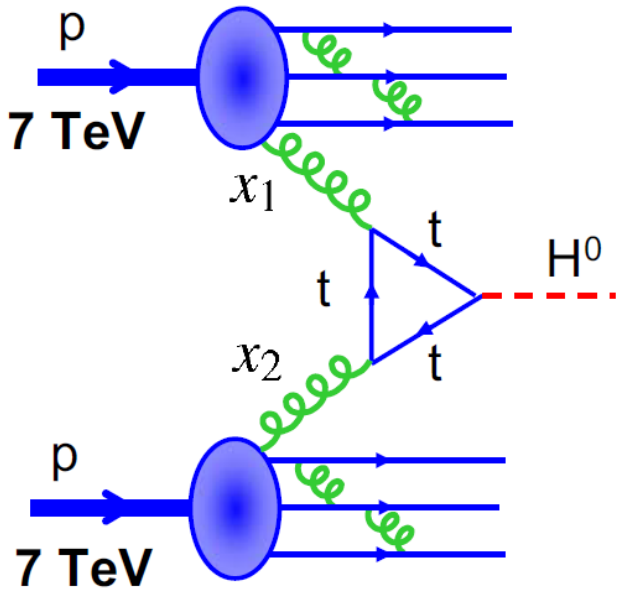


FIG. 19: ATLAS simulation of $gg \to H \to \gamma\gamma$ at LHC for $M_H = 120$ GeV and 30 fb^{-1} of data [42]. The right panel is the mass distribution after background subtraction, normalized from sidebands.

PRODUKCIJA HIGGSA NA LHC-u

- **Example:** Higgs production at the Large Hadron Collider LHC (2008-)
  - The LHC will collide 7 TeV protons on 7 TeV protons
  - However underlying collisions are between partons
  - Higgs production the LHC dominated by "gluon-gluon fusion"

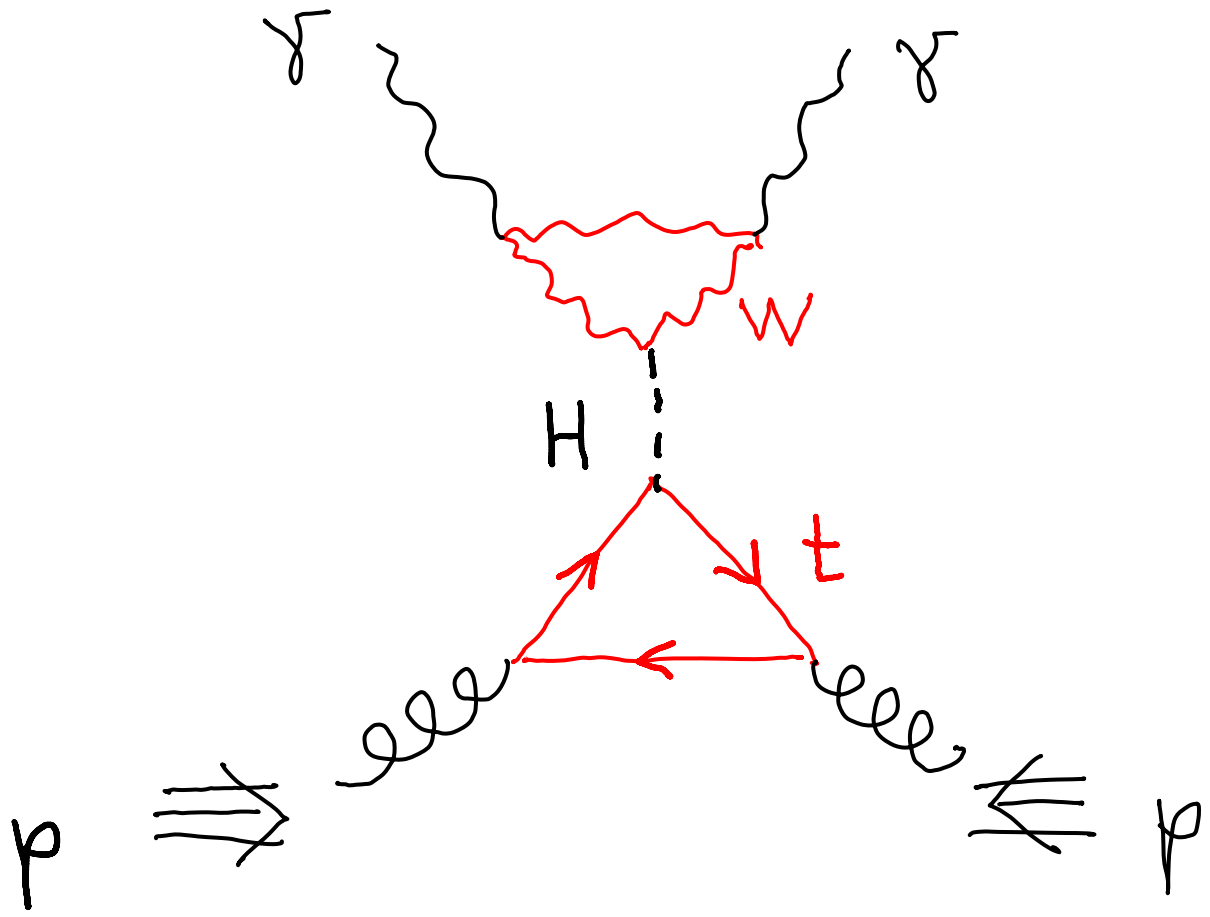


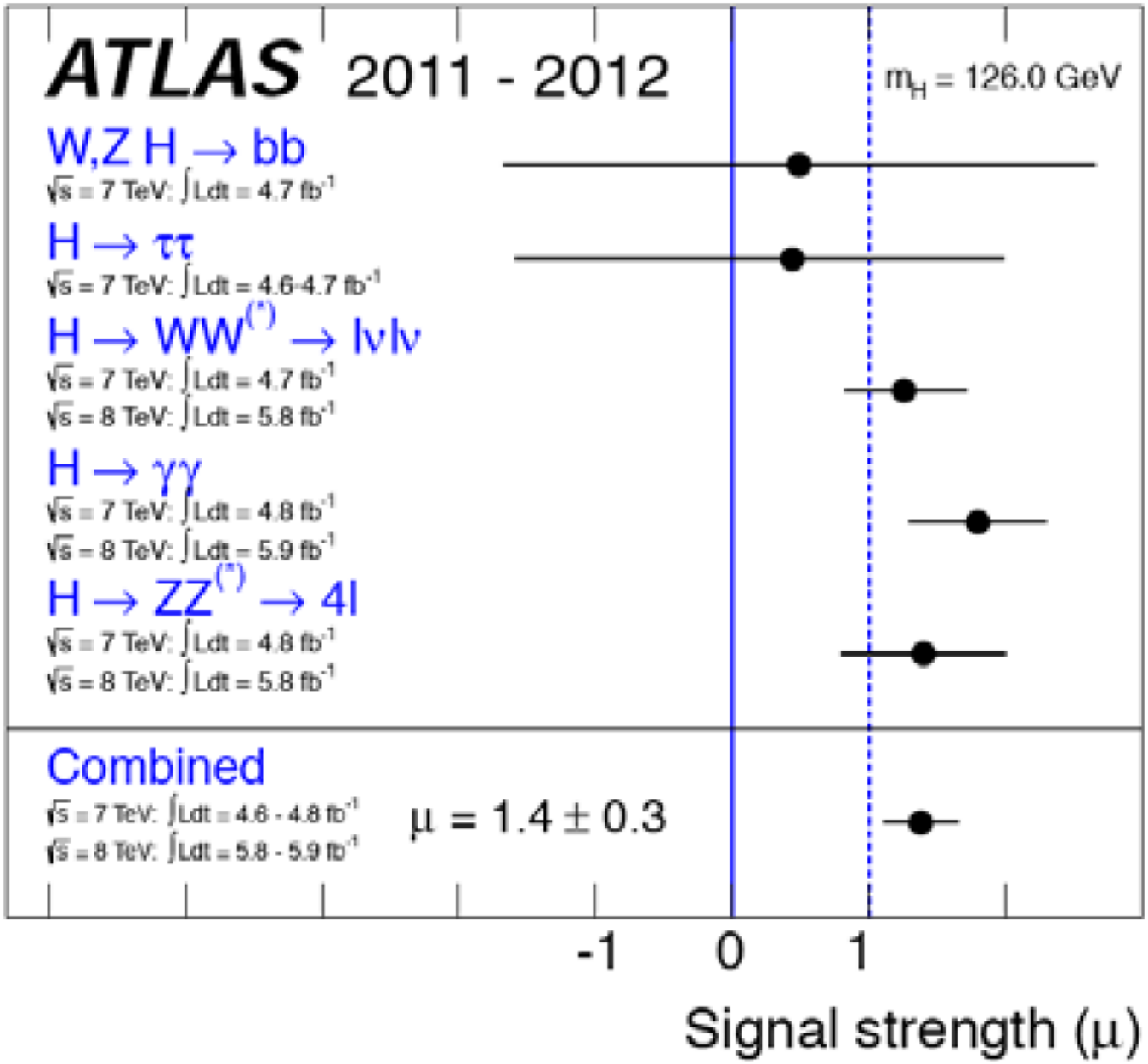
- Cross section depends on gluon PDFs

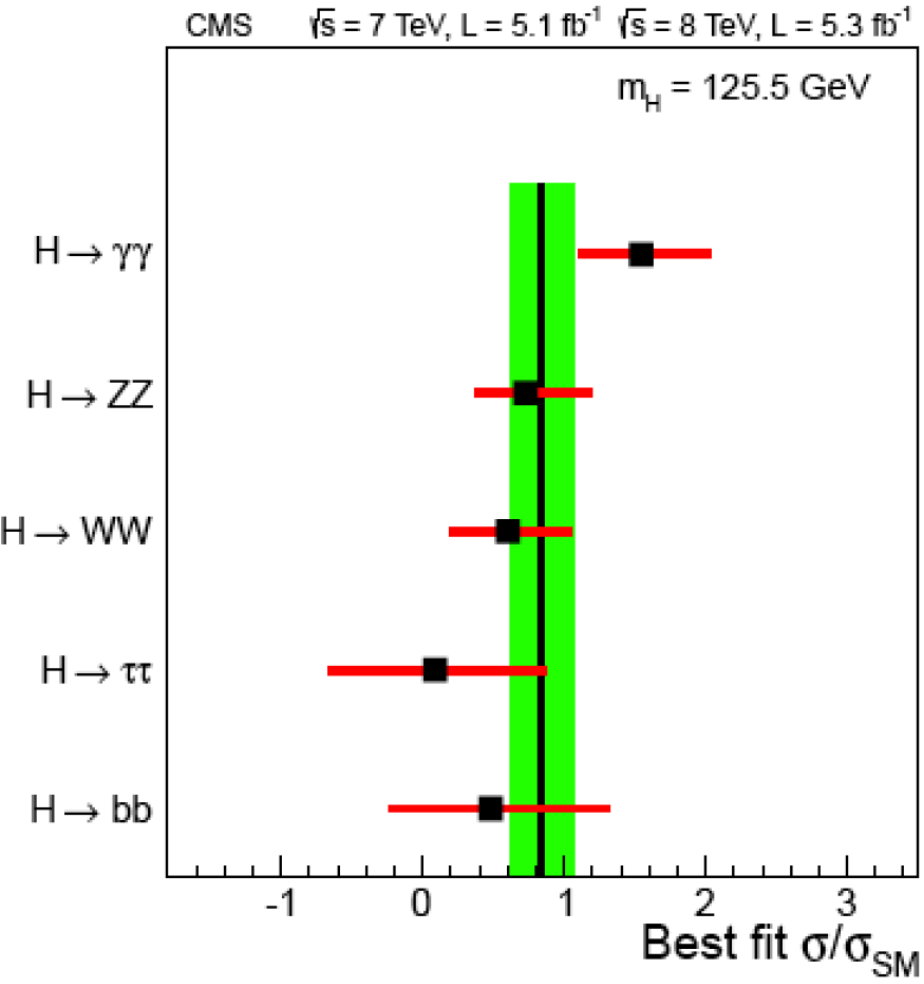
$$\sigma(pp \to HX) \sim \int_0^1 \int_0^1 g(x_1) g(x_2) \sigma(gg \to H) \mathrm{d}x_1 \mathrm{d}x_2$$

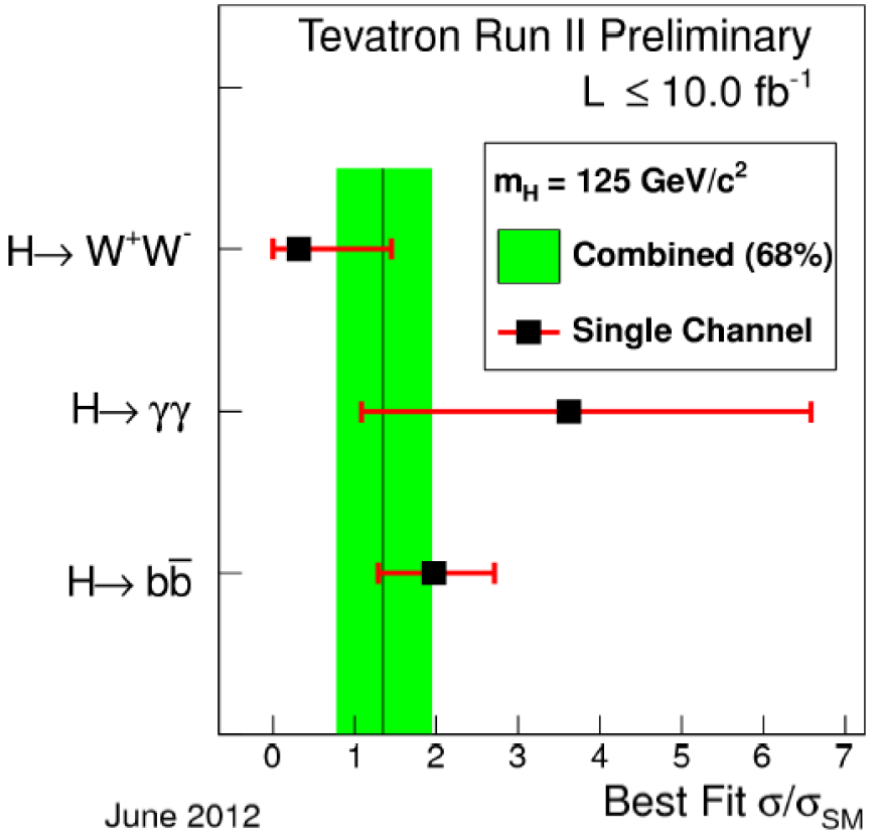
- Uncertainty in gluon PDFs lead to a ±5 % uncertainty in Higgs production cross section
- Prior to HERA data uncertainty was ±25 %

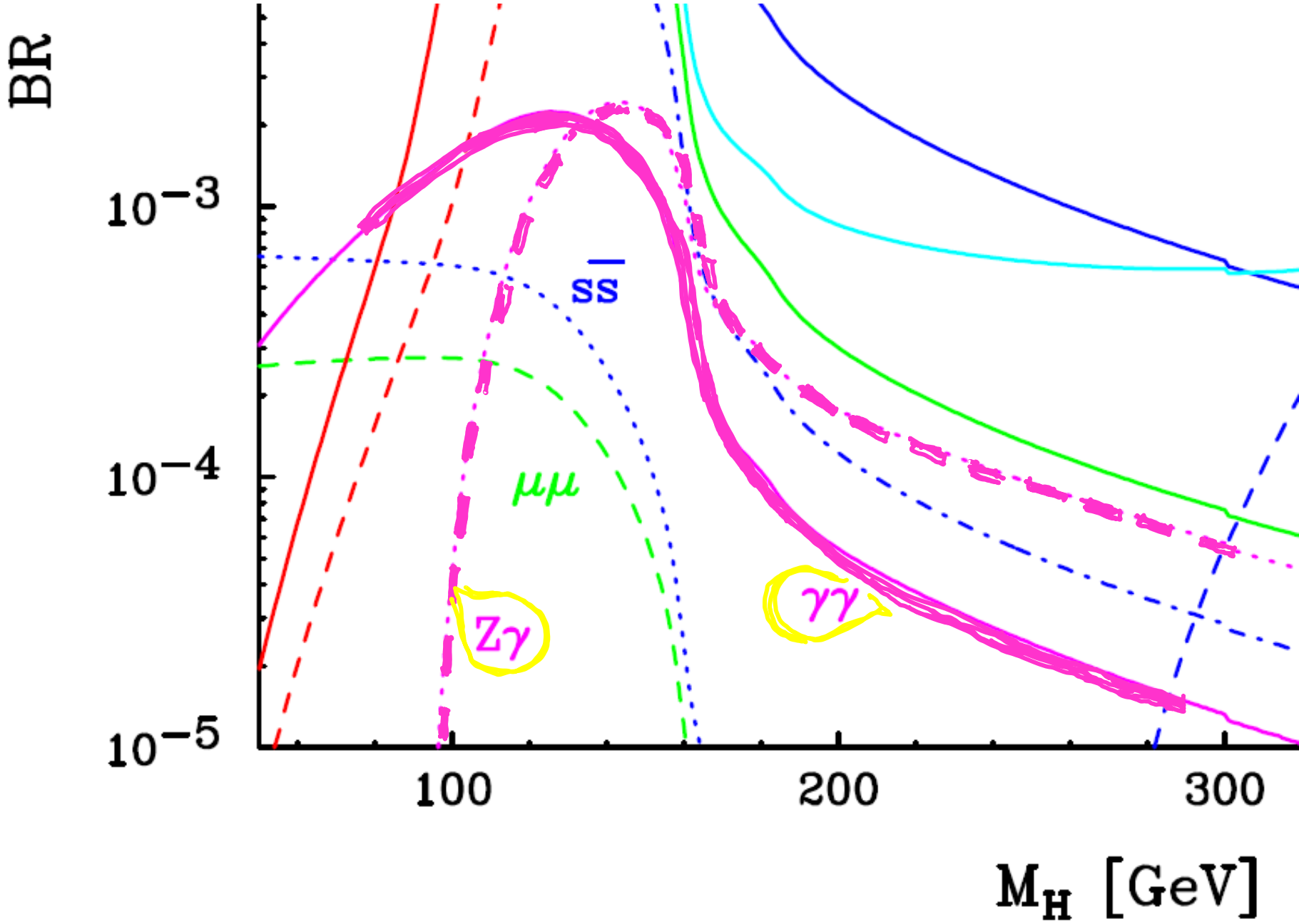
Produkcija i raspad higgsa putem kvantnih petlji

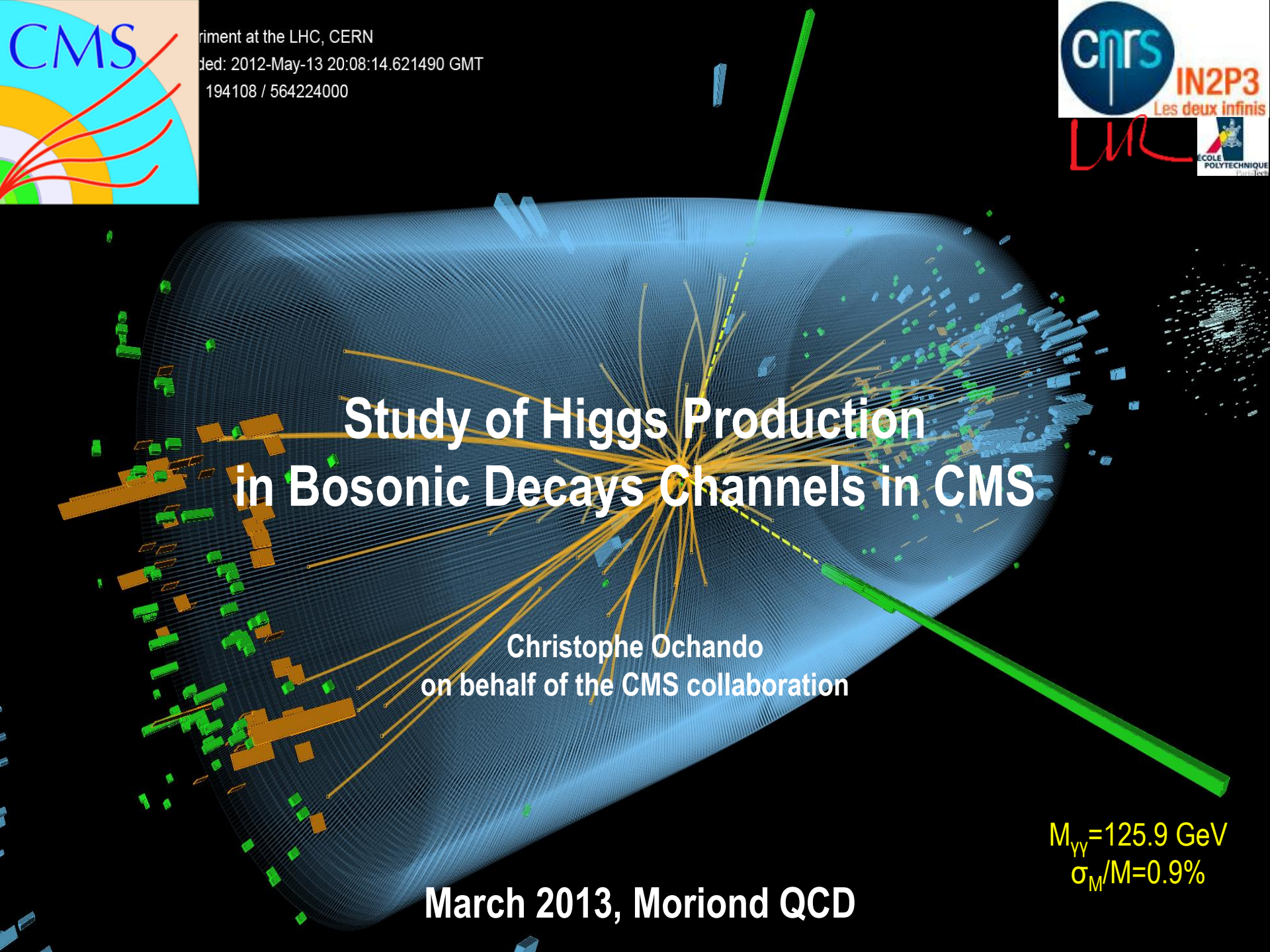



ATLAS 2011 - 2012
m_H = 126.0 GeV
W,Z H → bb
√s = 7 TeV: ∫Ldt = 4.7 fb⁻¹
H → ττ
√s = 7 TeV: ∫Ldt = 4.6-4.7 fb⁻¹
H → WW(*) → lνlν
√s = 7 TeV: ∫Ldt = 4.7 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.8 fb⁻¹
H → γγ
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.9 fb⁻¹
H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.8 fb⁻¹
Combined
√s = 7 TeV: ∫Ldt = 4.6 - 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.8 - 5.9 fb⁻¹
μ = 1.4 ± 0.3
-1
0
1
Signal strength (μ)


CMS
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
mH = 125.5 GeV
H → γγ
H → ZZ
H → WW
H → ττ
H → bb
-1
0
1
2
3
Best fit σ/σSM


Tevatron Run II Preliminary
L ≤ 10.0 fb-1
mH = 125 GeV/c2
Combined (68%)
Single Channel
H→ W+W-
H→ γγ
H→ bb̄
0
1
2
3
4
5
6
7
June 2012
Best Fit σ/σSM


BR
10^{-3}
10^{-4}
10^{-5}
$s\bar{s}$
$\mu\mu$
$Z\gamma$
$\gamma\gamma$
100
200
300
M_H [GeV]



Study of Higgs Production in Bosonic Decays Channels in CMS

Christophe Ochando
on behalf of the CMS collaboration

$M_{\gamma\gamma}$=125.9 GeV
σ_M/M=0.9%

March 2013, Moriond QCD

Najosjetljiviji kanali

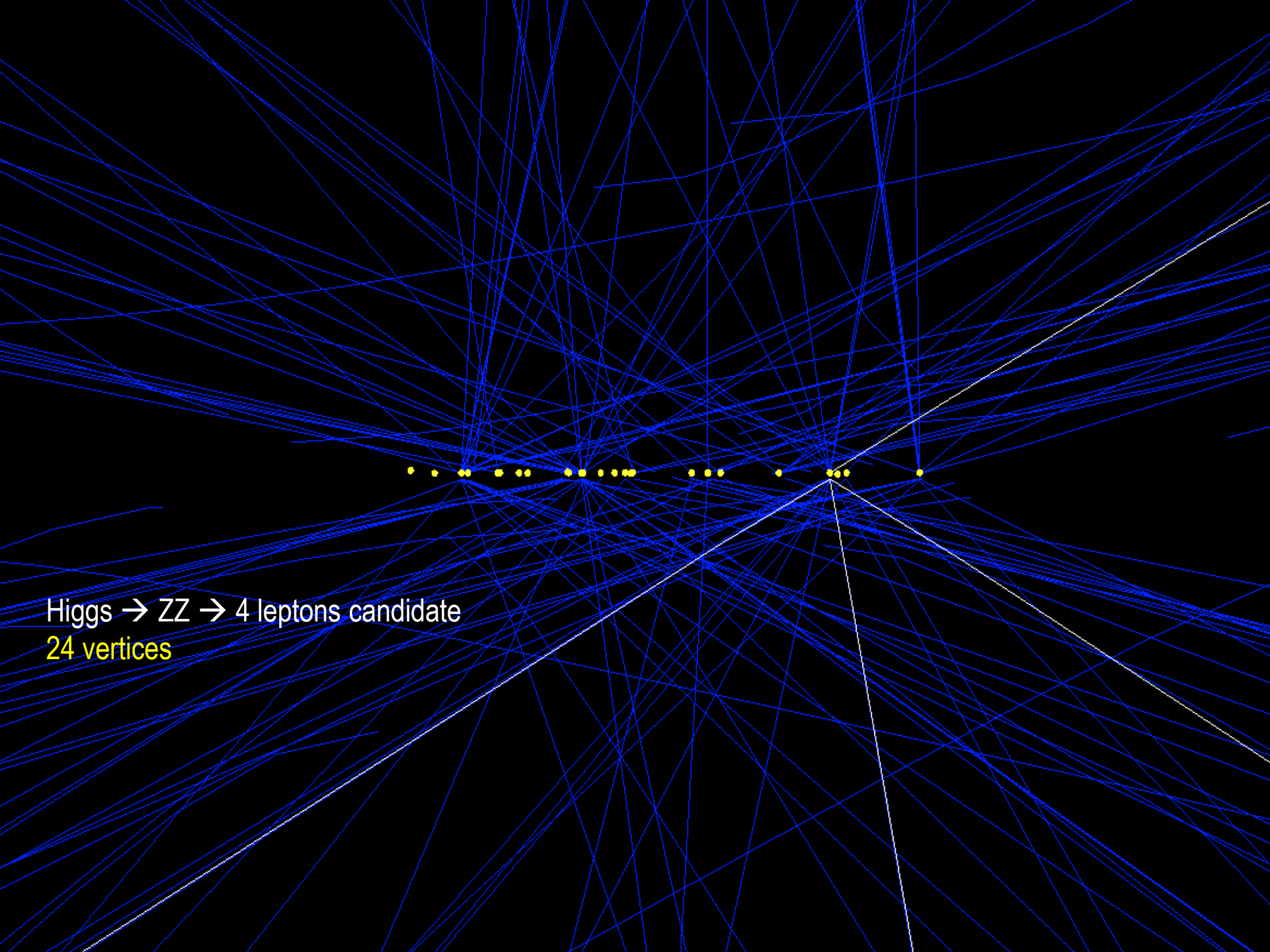
	m_H range (GeV)	m_H resolution	L (fb^{-1}) [7+8 TeV]	
NEW $H \to ZZ \to 4l$	110-1000	1-2%	5.1 + 19.6	High Resolution
NEW $H \to \gamma\gamma$	110-150	1-2%	5.1 + 19.6	
NEW $H \to WW \to 2l2nu$	110-600	20%	4.9 + 19.5	Large yields

- In back-up:

NEW	$WH \to WWW \to 3l\nu$	110-200	4.9 + 19.5
NEW	$H \to Z\gamma$	120-150	5.0 + 19.6
	$VH \to qq'2l2\nu$	120-190	4.9
	$H \to ZZ \to 2l2q$	130-600	4.6
	$H \to ZZ \to 2l2\nu$	200-600	5.1 + 5
NEW	$H \to ZZ \to 2l2\tau$ (with 4l at high mass)	180-1000	5.1 + 19.3
	$H \to WW \to qq'l\nu$	170-600	5.0+12

Rare mode

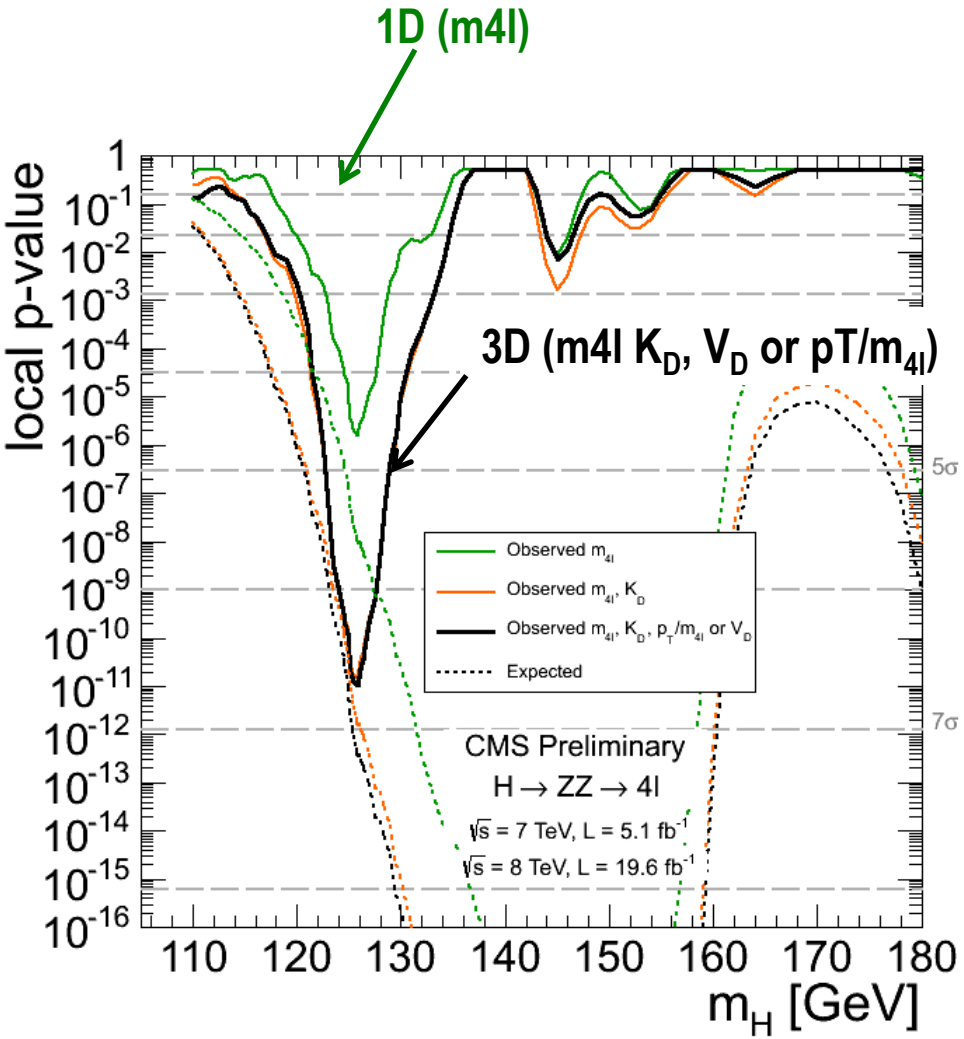
High mass only

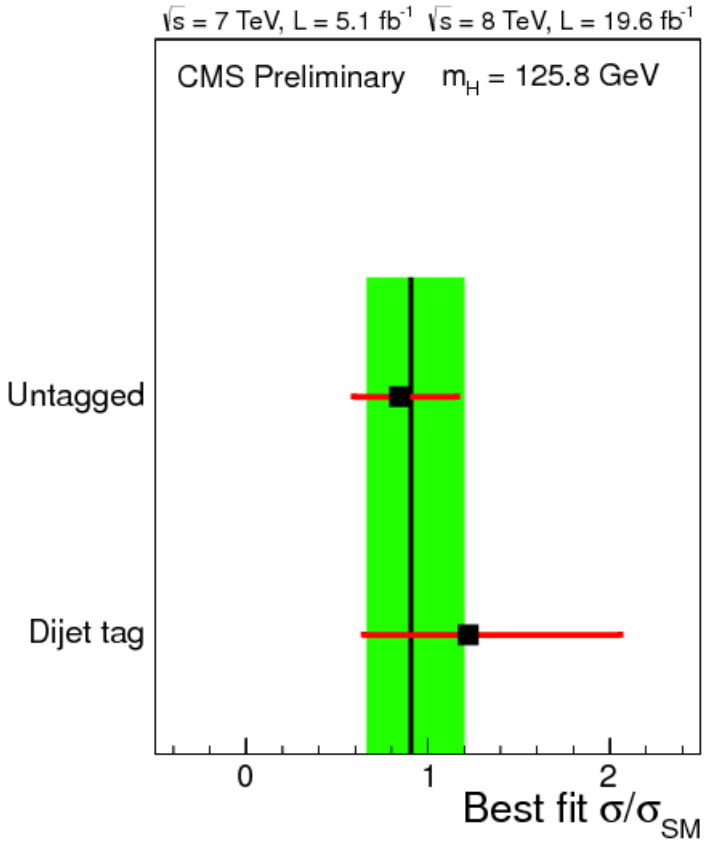

Higgs → ZZ → 4 leptons candidate
24 vertices

Rezultali za H→ZZ →4l:

Significance @ 125.8 GeV: 6.7 σ (7.2 expected)
with 3D (m_{4l}, K_D, V_D or pT/m_{4l}) model

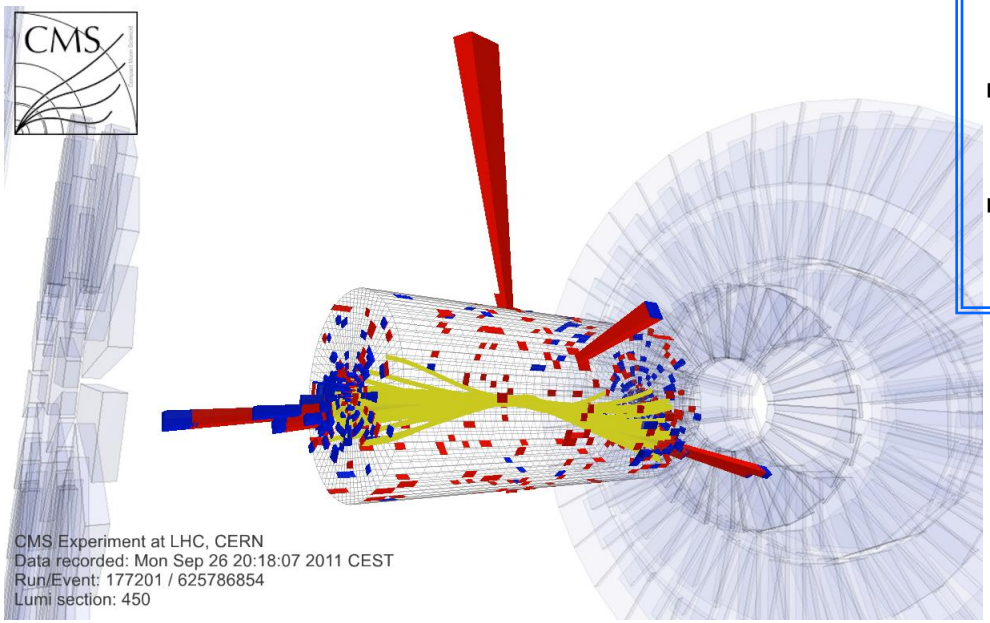
σ/σ_{SM} @ 125.8 GeV = 0.91 $^{+0.30}_{-0.24}$





$H \rightarrow \gamma\gamma$: Exclusive categories

- In addition to the untagged categories, high S/B categories are defined using additional objects in the event
  - Improve significantly the reach to measure Higgs couplings



- **Di-jet**:
  - 2 categories (loose/tight) with increasing VBF purity (loose ~50%, tight ~80%).
  - MVA analysis uses a dijet BDT-based selection (validated using Z+jets events)

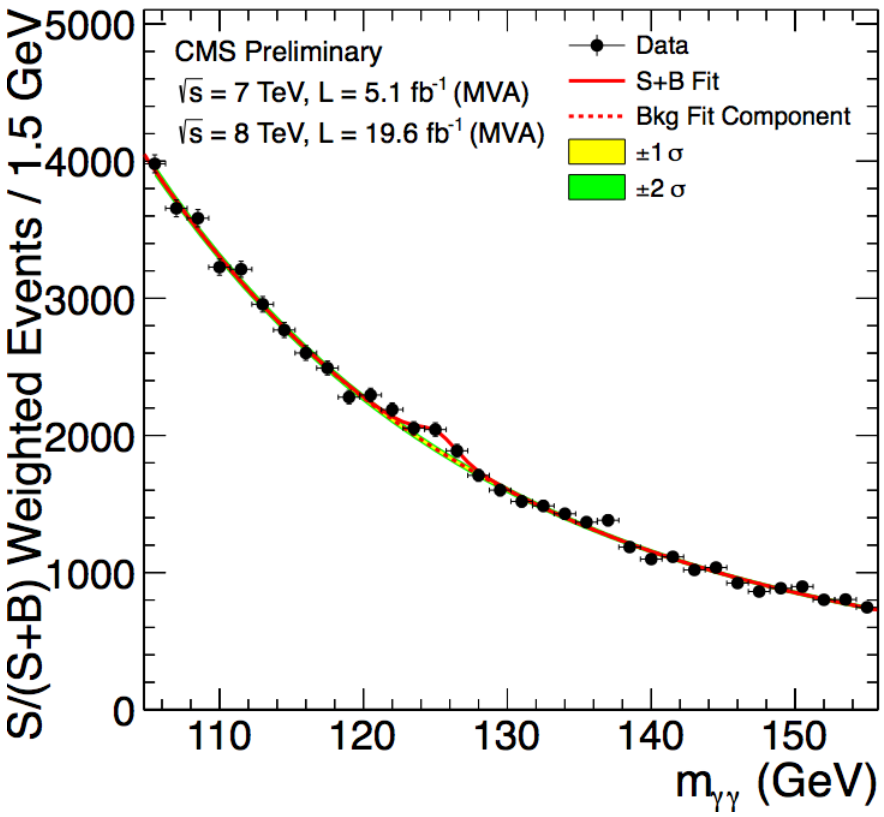
- Additional **leptons** (e or μ p_T>20 GeV)
- **MET** (>70 GeV): lepton categories have negligible gg contamination, 20% for MET

Events are assigned exclusively to a category following the S/B ordering:

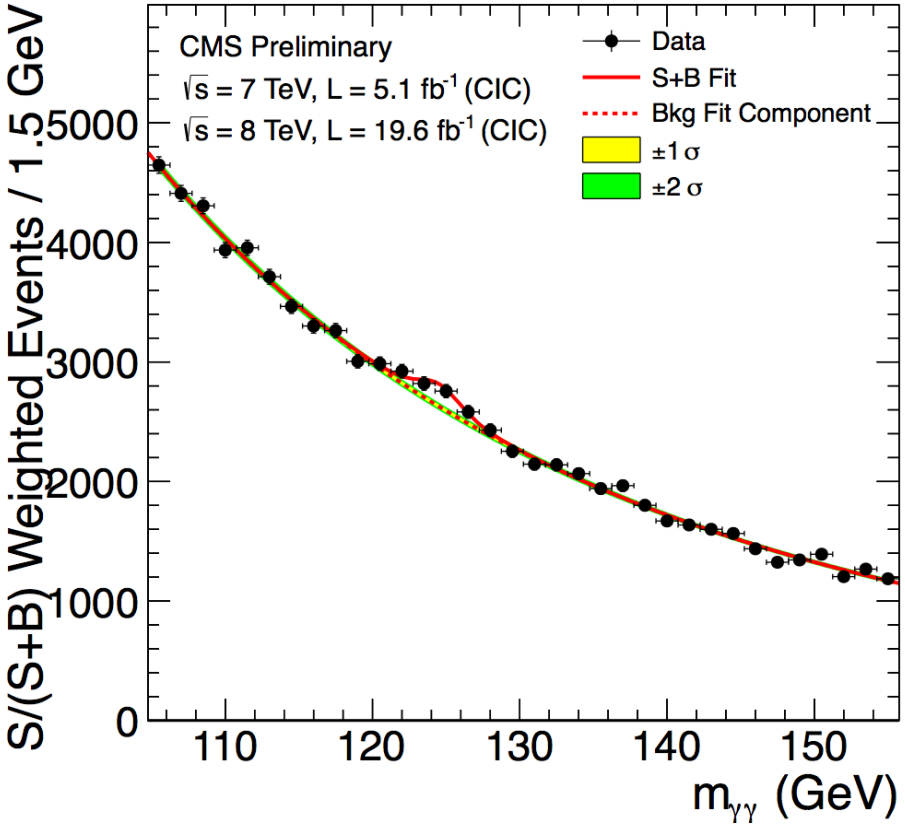
Muon → Electron → Dijet → MET → Untagged

$H \to \gamma\gamma$: Combined mass plot: 7+8

MVA mass-factorized



Cut-based

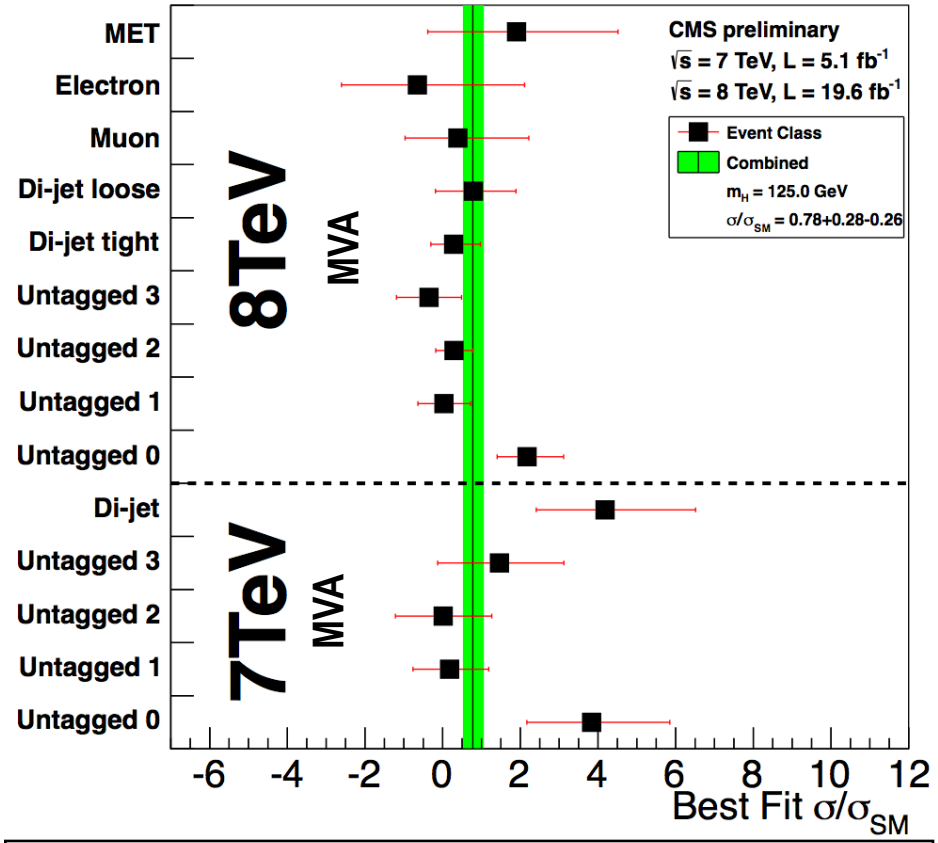


Bump at ~125 GeV consistent with expectations

Each event category is **weighted by its S/(S+B)** only for visualization purpose

H → WW: Results (channel

MVA mass-factorized

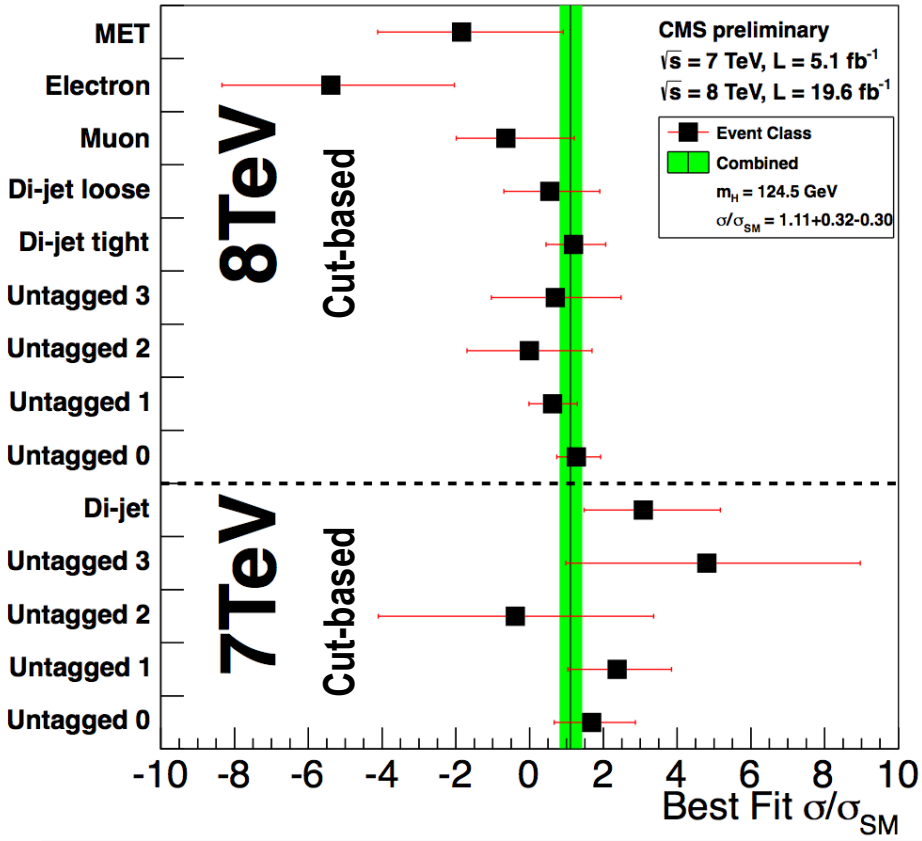


7+8 TeV: σ/σ_{SM} @ 125.0 GeV = $0.78\ ^{+0.28}_{-0.26}$

7 TeV: σ/σ_{SM} @ 125.0 GeV = $1.69\ ^{+0.65}_{-0.59}$

8 TeV: σ/σ_{SM} @ 125.0 GeV = $0.55\ ^{+0.29}_{-0.27}$

Cut-based



7+8 TeV:σ/σ_{SM} @ 124.5 GeV = $1.11\ ^{+0.32}_{-0.30}$

7 TeV: σ/σ_{SM} @ 124.5 GeV = $2.27\ ^{+0.80}_{-0.74}$

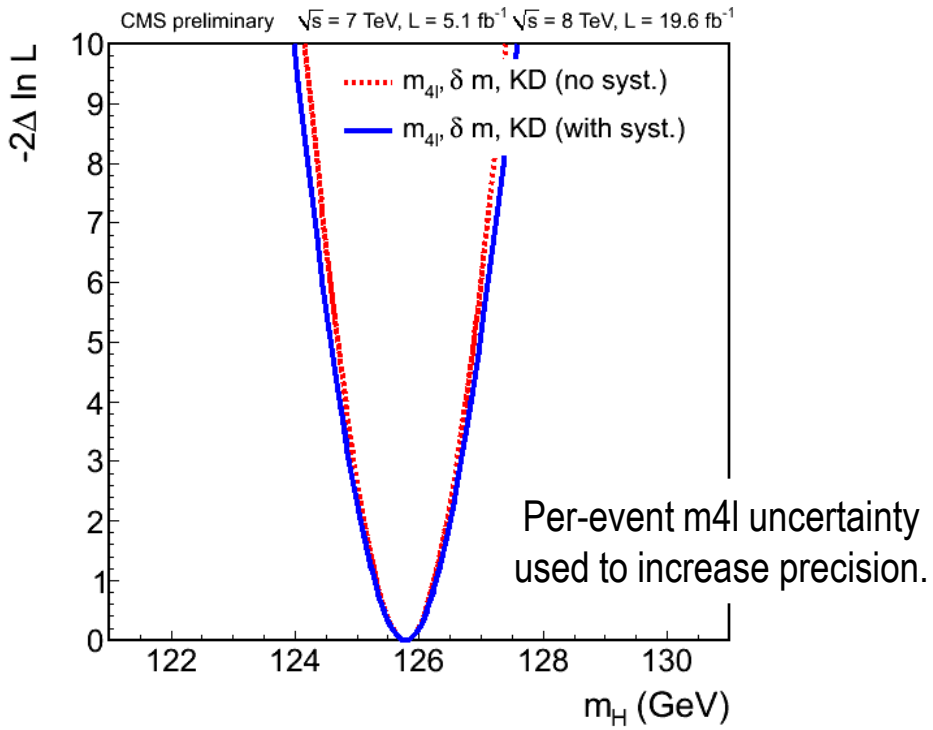
8 TeV: σ/σ_{SM} @ 124.5 GeV = $0.93\ ^{+0.34}_{-0.32}$

- Despite the same names, the untagged categories in MVA and Cut-basd are not equivalent

Mass measurement

H→ZZ→ 4l

- Lepton momentum scale & resolution validated with Z, J/ψ, and Υ→ll samples.
- m4l uncertainties due to lepton scale: 0.1% (4μ), 0.3% (4e)

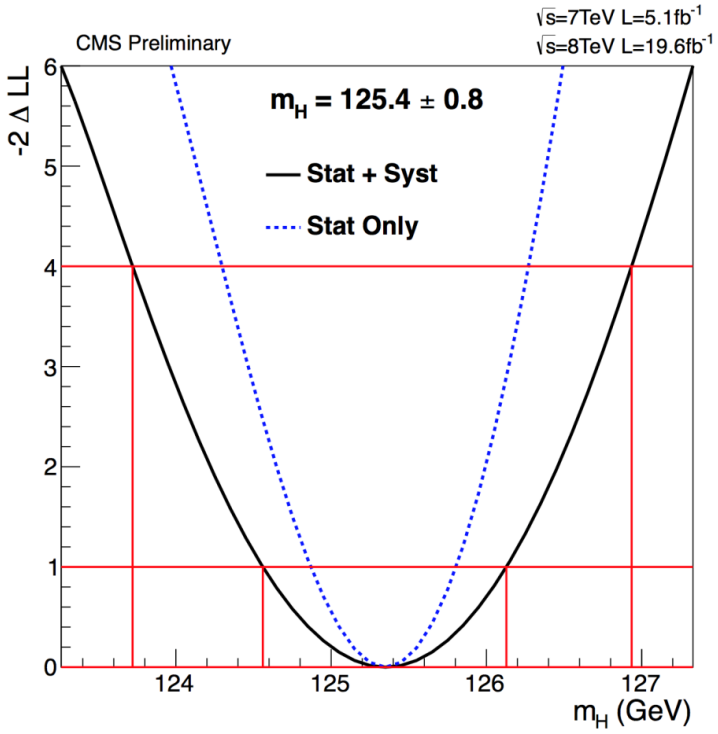


Per-event m4l uncertainty used to increase precision.

$m_H = 125.8 \pm 0.5$ (stat.) $\pm$ 0.2 (syst.)

H→γγ

- Systematic errors dominated by overall photon energy scale: 0.47%
(mostly coming from extrapolation from Z→H and e→γ)



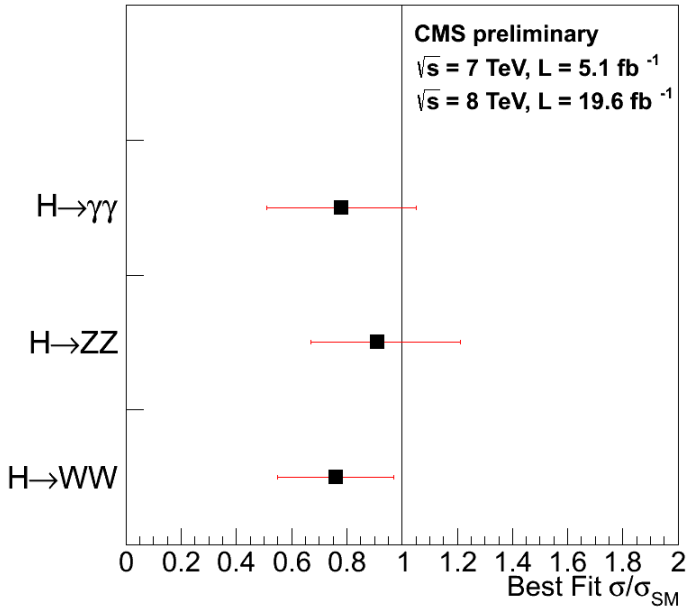
$m_H = 125.4 \pm 0.5$ (stat.) $\pm$ 0.6 (syst.)

Measurements in the two channels are well compatible.

Evidence for SM Higgs candidate at ~mH=126 GeV is growing

Conclusion

- 3 major H→VV channels updated with full dataset. + rare modes (in back-up)



- Significance of observation:
  - **H→ZZ→4l: 6.7 σ (7.2 exp.)**
  - **H→WW: 4.1 σ (5.1 exp.)**
  - **H→γγ: 3.2 σ (4.2 exp)**

So far, all individual channels are consistent with the SM, within uncertainties (statistically dominated)

- Moving to precise measurement of properties:
  - Mass: **$m_H = 125.8 \pm 0.5$ (stat.) $\pm$ 0.2 (syst.)** H→ZZ→4l
  - **$m_H = 125.4 \pm 0.5$ (stat.) $\pm$ 0.6 (syst.)** H→γγ
  - Production Mechanisms:
  - Spin-Parity hypothesis tests:

See Andrew's talk.