Measurement of Initial State Radiation @ CDF

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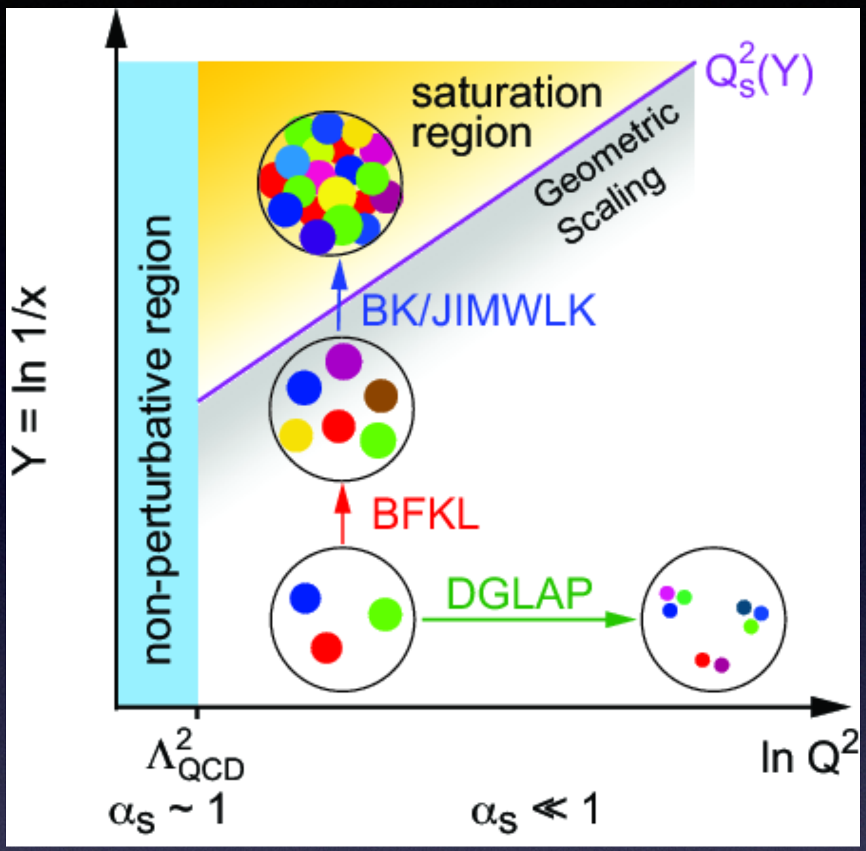
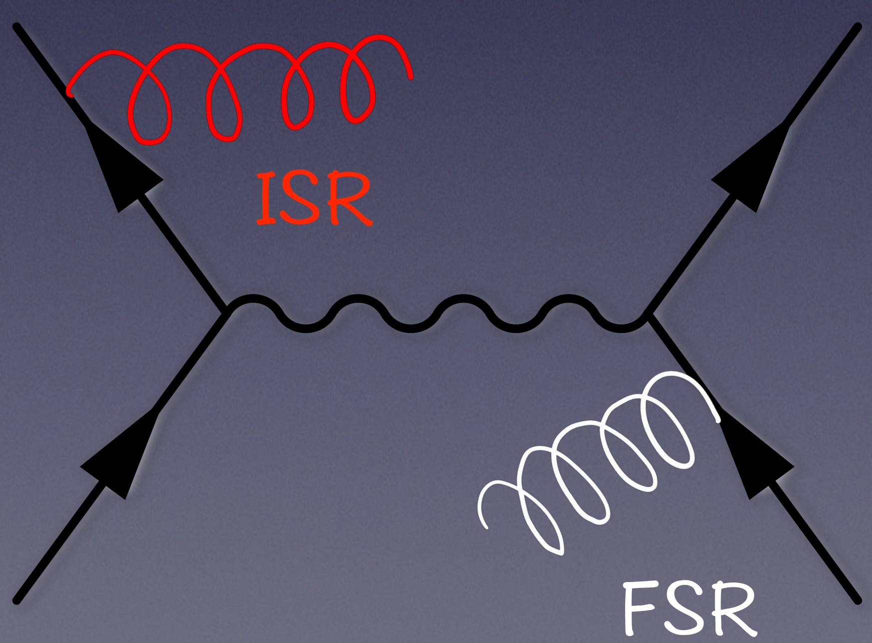
QCD in hadron collider



- Hadron is a complex bound state of quarks and gluons, and their dynamics (QCD) is a non-abelian gauge group theory, SU(3)
- Hadron collisions at high energy bring a variety of gluon radiation before and after the hard scattering
  - Initial state radiation (ISR): space-like shower, radiation from the incoming quarks
  - Final state radiation (FSR): time-like shower, radiation from the outgoing partons
- QCD evolves depending on which direction you look at:
  - Focus on the QCD evolution with Q^2 via the DGLAP equation: MC generators employ this evolution



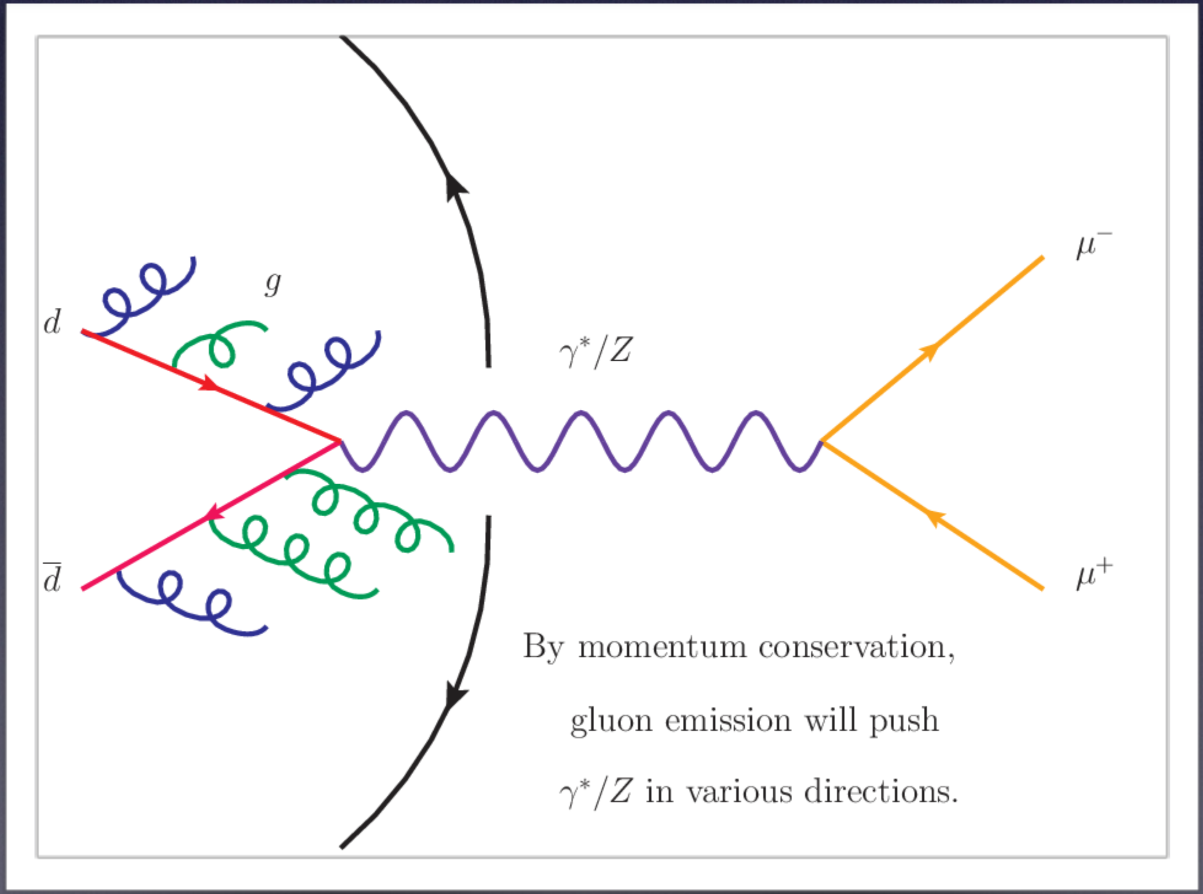
$$\frac{dq(x,Q^2)}{d\log Q^2} = \frac{\alpha_S(Q^2)}{2\pi}\int_x^1 \frac{dy}{y} q(y,Q^2) P\left(\frac{x}{y}\right)$$

Parton density

Splitting function

ISR measurement using Drell-Yan

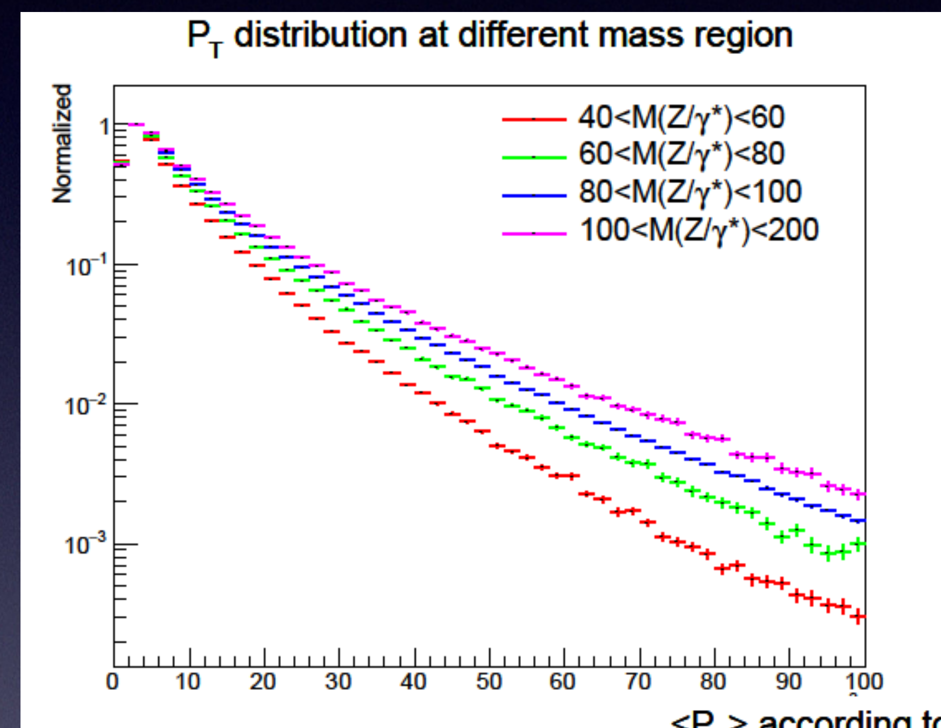
- QCD Initial State Radiation (ISR) has been a well-known but least-studied subject ever since the HERA experiments
  - Analyses deal with the inevitable uncertainty from ISR
- This measurement quantifies the effect of ISR as a function of collision energy and gives an idea of estimating the ISR for any physics processes at high energy collision
- Drell-Yan $Z/\gamma^* \rightarrow l^+l^-$ process restricts the gluon radiation being originated from incoming quarks
  - The transverse momentum of the process is a good observable to quantify the ISR



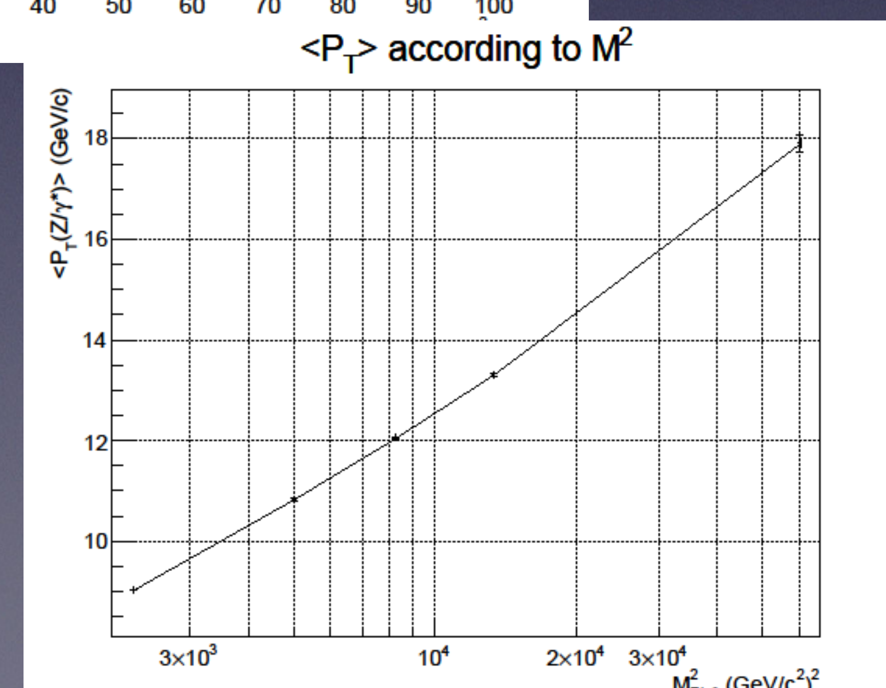
Strategy of the Measurement

$$\frac{dq(x,Q^2)}{d\log Q^2} = \frac{\alpha_S(Q^2)}{2\pi}\int_x^1 \frac{dy}{y}\, q(y,Q^2)\, P\left(\frac{x}{y}\right) \rightarrow \frac{\langle p_T^{\ell\ell}\rangle}{\log \langle m_{\ell\ell}^2\rangle}$$

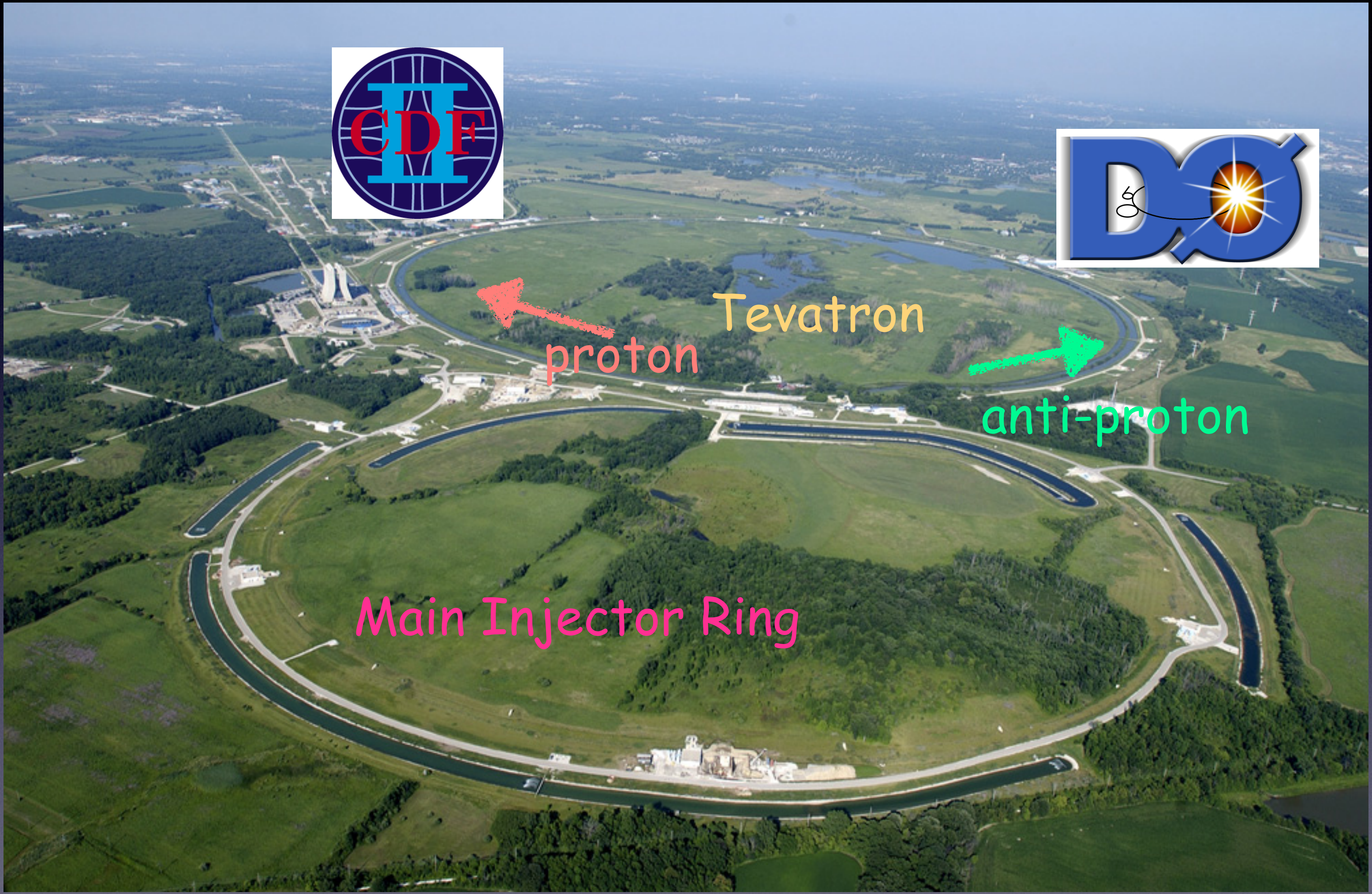
- The Drell-Yan mass square (m_{ll}^2) corresponds to the Q^2
- The amount of ISR is quantified by $<p_T^{ll}>$
- Assumption is that the $<p_T^{ll}>$ grows as the m_{ll} goes higher in the DY sample
- For simplifying the relation
  - Use 5 DY mass bins (GeV) for $<p_T^{ll}>$: [40,60,80,100,200,350]
  - Too hard ISR removed: $p_T^{ll} < 100$ GeV



PYTHIA8



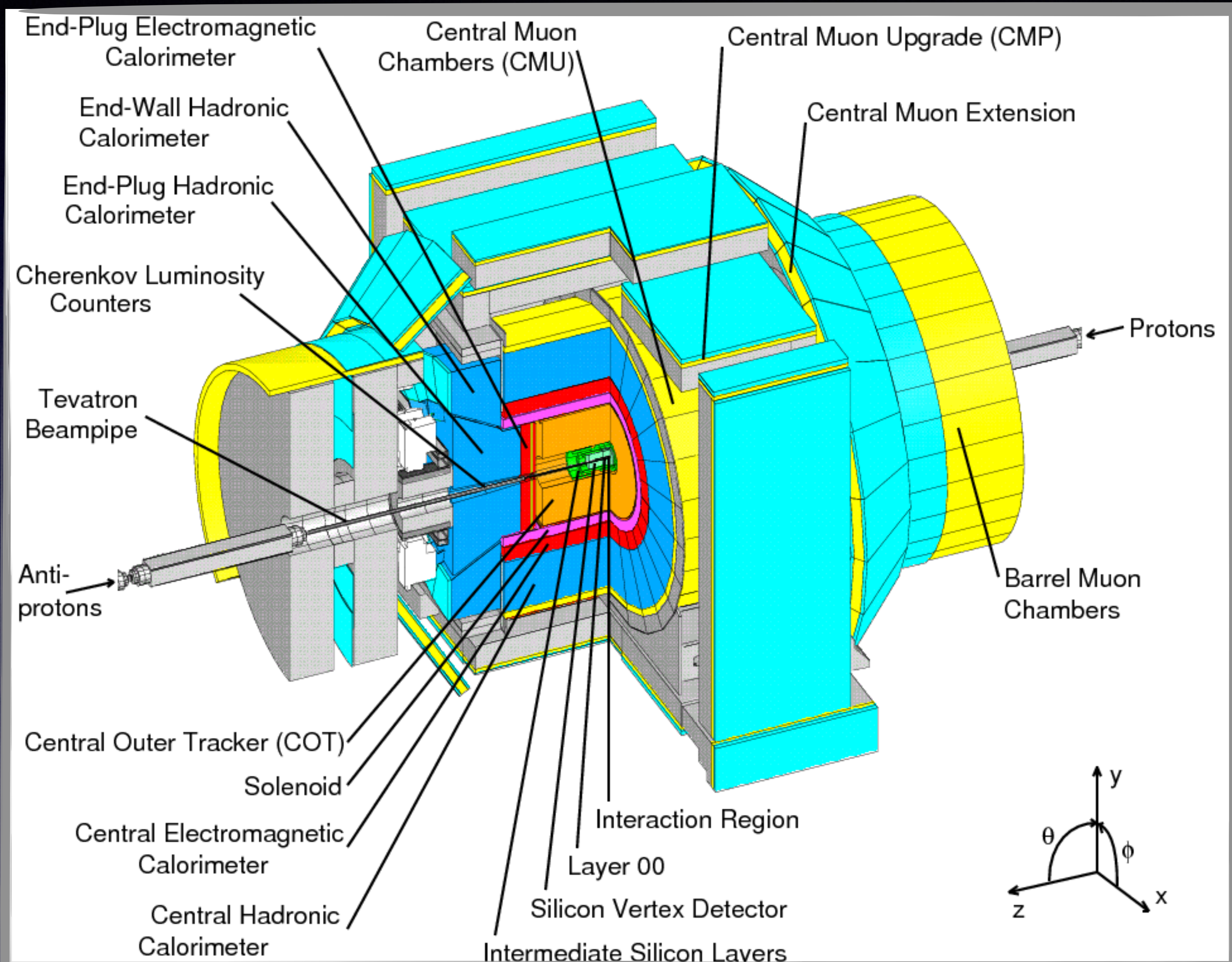
Collider Detector at Fermilab @ Tevatron



Run2 operation 1/3/2001—30/9/2011

Tevatron delivered ~12 fb^{-1} to each experiment, ~10 fb^{-1} recorded

The CDF II detector



https://doi.org/10.1016/j.nima.2013.07.015

Muon Chambers	$|\eta|$ Coverage
CMU/CMP	<0.6
CMX	0.6–1.0
BMU	1.0–1.5

EM Calorimeter	$|\eta|$ Coverage
Central	<1.1
End-Plug	1.1–3.64

DiLepton Event Selection

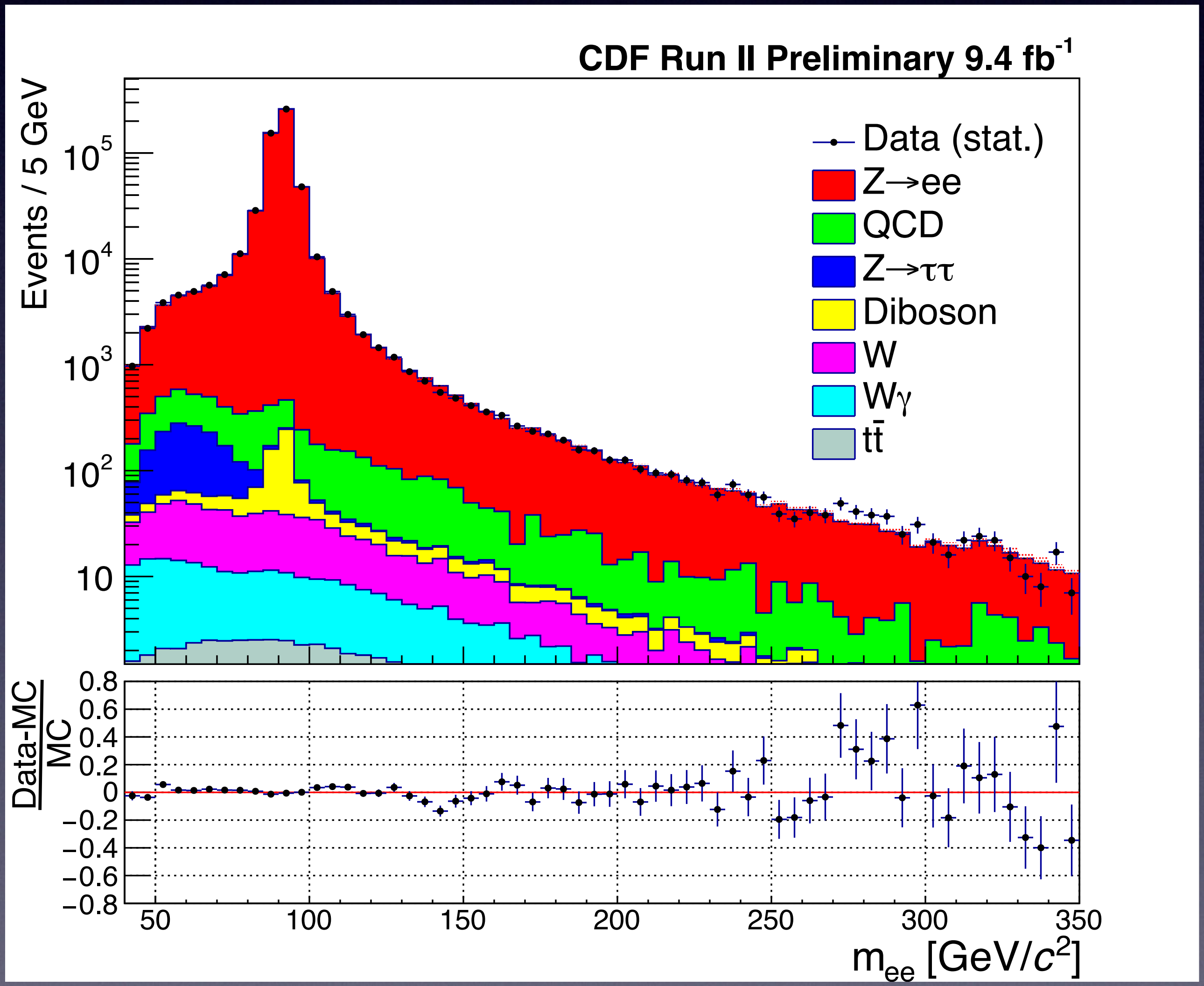
CDF Run II data (9.4 fb-1) with proton-antiproton collisions at 1.96 TeV

	$\mu\mu$ channel	ee channel
Trigger	Single Muon	Single Electron || double e/γ
Lepton	Opposite signed $\mu\mu$ - $p_T(\mu 1)>20$ GeV - $p_T(\mu 2)>12$ GeV - $\|\eta\|<1.5$	Central-Central - Opposite signed - p_T(e1,e2)>25,15 GeV, $0.05<\|\eta\|<1.05$ Central-Plug - Central: $p_T>20$ GeV, $0.05<\|\eta\|<1.05$ - Plug: $p_T>20$ GeV, $1.2<\|\eta\|<2.8$ Plug-Plug - p_T(e1,e2)>25 GeV, $1.2<\|\eta\|<2.8$ - Require electron pair from same side
Event Cut	$p_T(\mu\mu)<100$ GeV	p_T(ee)<100 GeV, Missing $E_T<40$ GeV, FSR cut*
Background	CDF simulation (PYTHIA6): Z→$\tau\tau$,W,Wγ,dibosons, tt Data-driven: multi-jet QCD	
Additional corrections	Number of vertex / Vertex position / Lepton energy/momentum / Z boson p_T*	

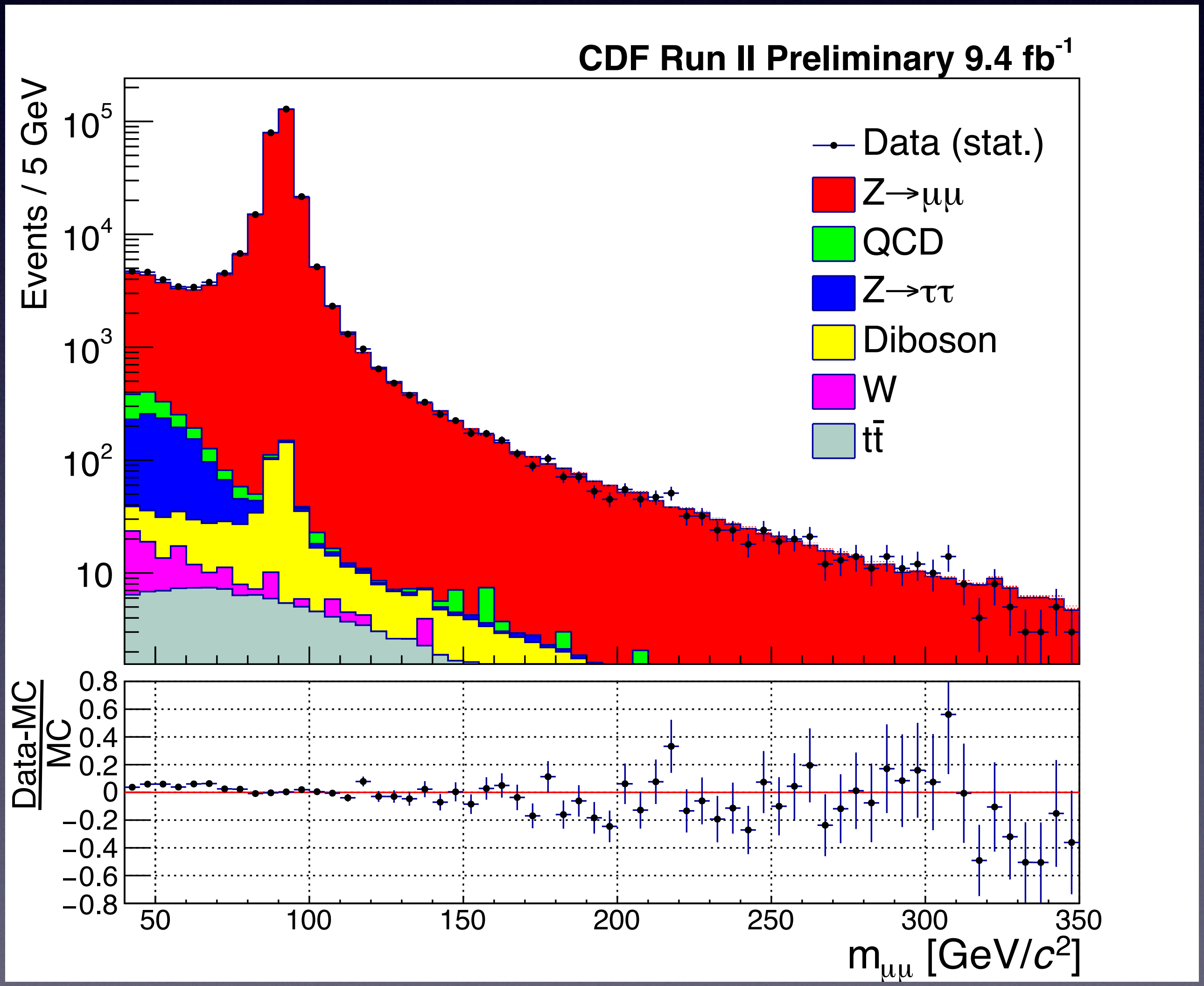
*at backup

DiLepton Mass

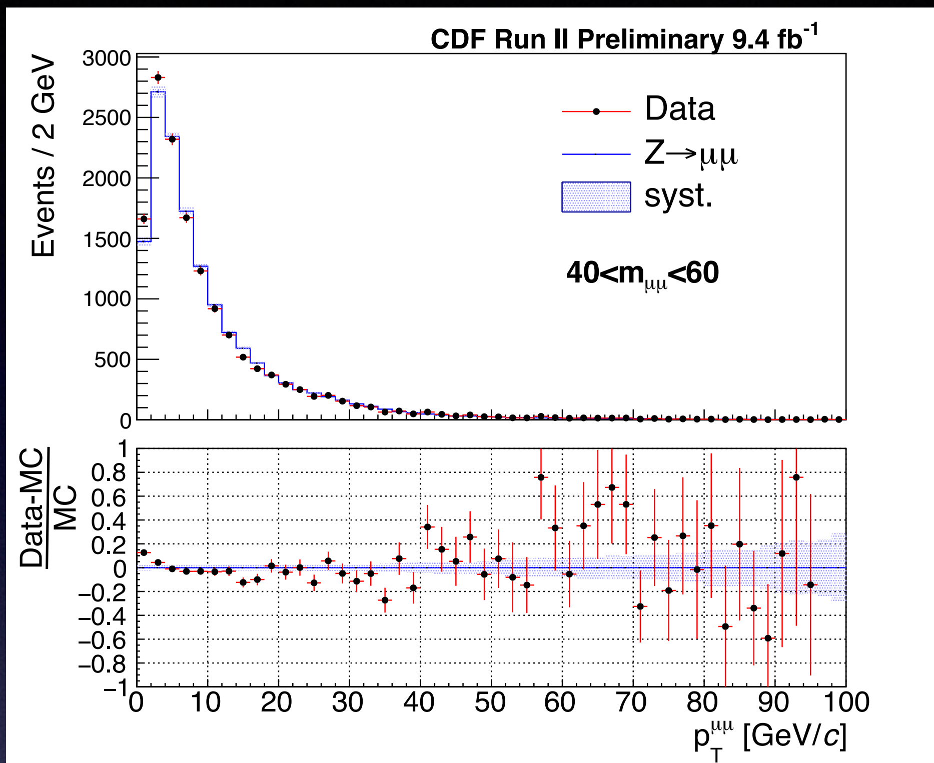
ee channel

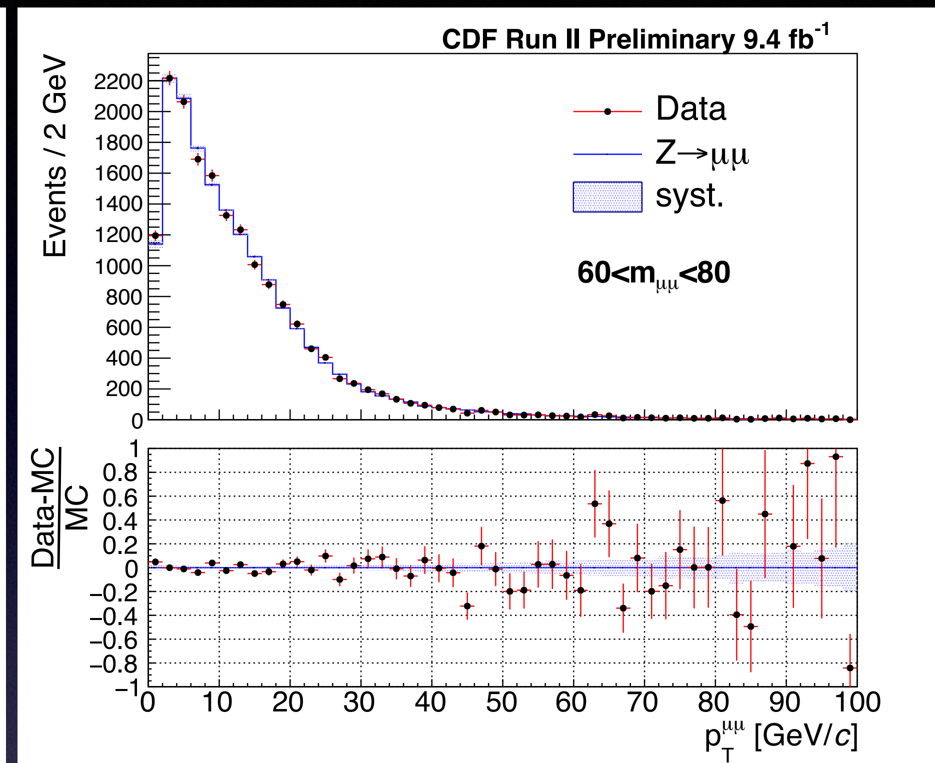


$\mu\mu$ channel



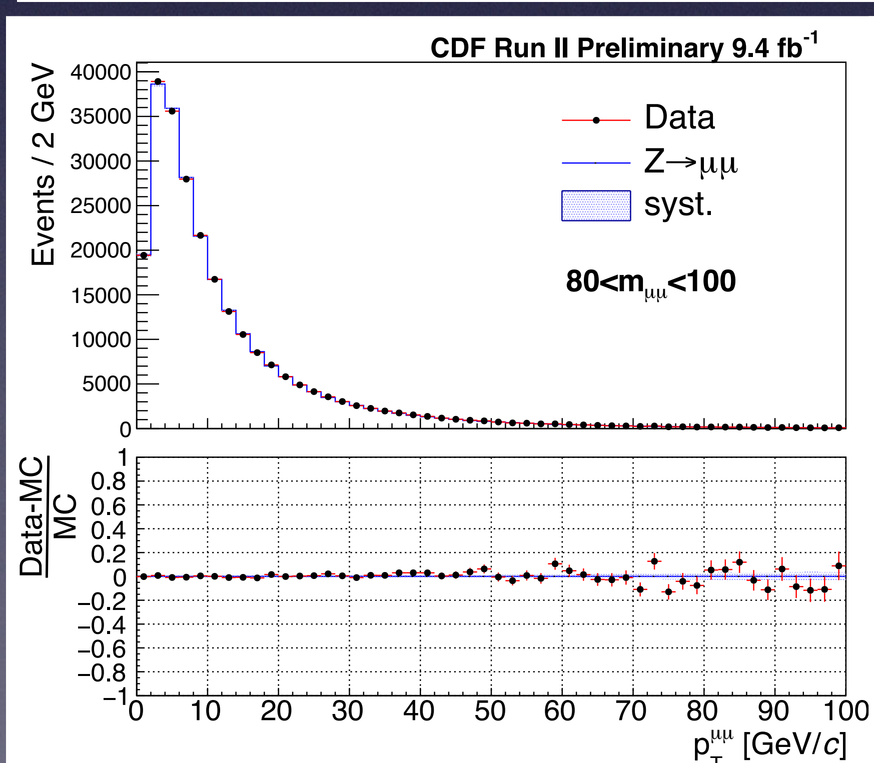
DiLepton pT

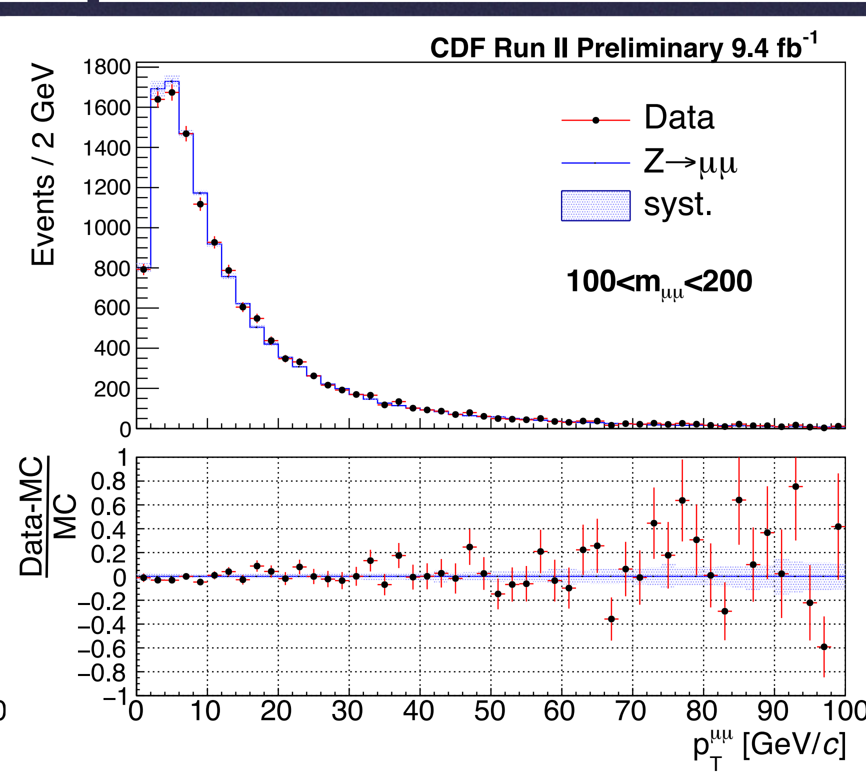


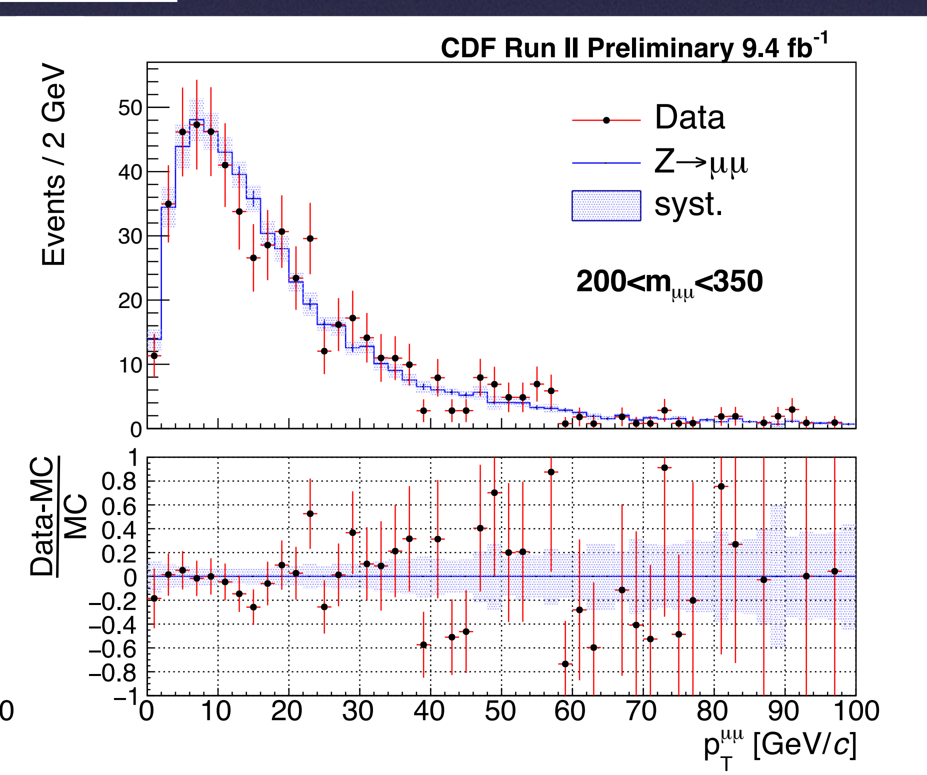


μμ channel

Other SM backgrounds subtracted from Data







Correction: reconstruction→generator

- Correction derived from Drell-Yan MonteCarlo sample:
  - Multiplicative correction factor
  - Reconstruction→generator level

$$\langle p_T \rangle^{corr.}_{data} = \frac{\langle p_T \rangle^{gen.}_{MC}}{\langle p_T \rangle^{reco.}_{MC}} \times \langle p_T \rangle^{reco.}_{data}$$

- The correction includes:
  - Removing the effect from detector resolution and efficiency
  - Restoring the missing momentum due to QED FSR
  - Acceptance

Systematic Uncertainties

μμ channel

Mass bin (GeV)	[40,60]	[60,80]	[80,100]	[100,200]	[200,350]
Statistical Unc.(%)	0.96	0.73	0.22	0.95	3.79
Systematic Unc.(%)	1.31	1.33	0.26	0.91	2.84
ISR model	0.93	0.93	0.24	0.52	2.38
QED FSR model	0.87	0.93	0.03	0.18	0.41
Momentum scale	0.11	0.13	0.04	0.20	0.85
Momentum resolution	0.07	0.06	0.08	0.68	1.20
Background norm.	0.28	0.10	0.03	0.16	0.25

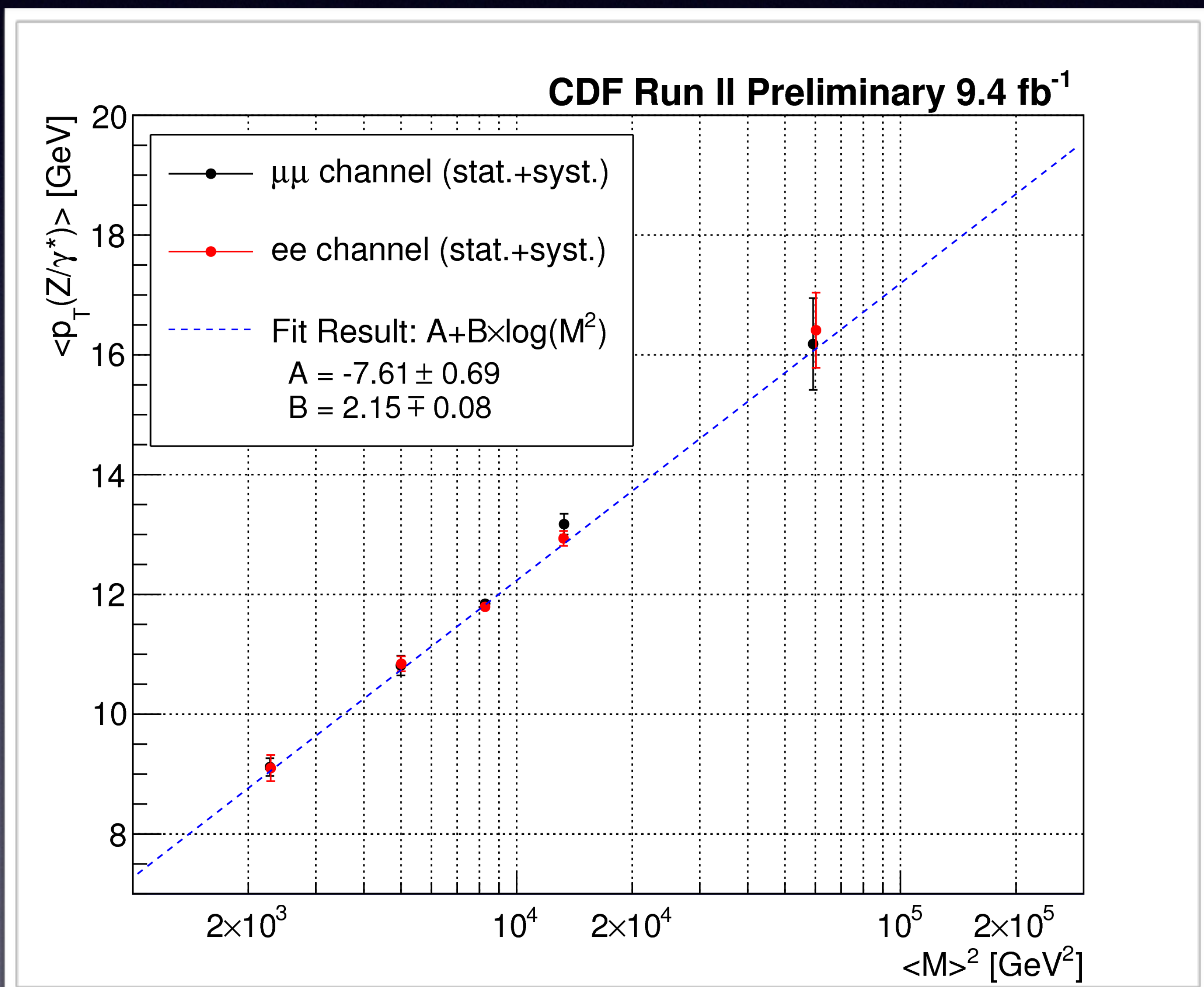
ee channel

Mass bin (GeV)	[40,60]	[60,80]	[80,100]	[100,200]	[200,350]
Statistical Unc.(%)	1.38	0.70	0.16	0.72	3.44
Systematic Unc.(%)	1.96	0.91	0.17	0.63	1.67
ISR model	1.26	0.51	0.13	0.15	1.07
QED FSR model	1.39	0.72	0.05	0.22	0.67
Energy scale	0.11	0.07	0.02	0.08	0.21
Energy resolution	0.02	0.02	0.08	0.10	0.15
Background norm.	0.57	0.21	0.03	0.56	1.06

Dominant Sources:

- ISR model: variation of Z boson p_T correction
- QED FSR model: comparison between PYTHIA6 and PHOTOS++

Results



μμ channel

(GeV)

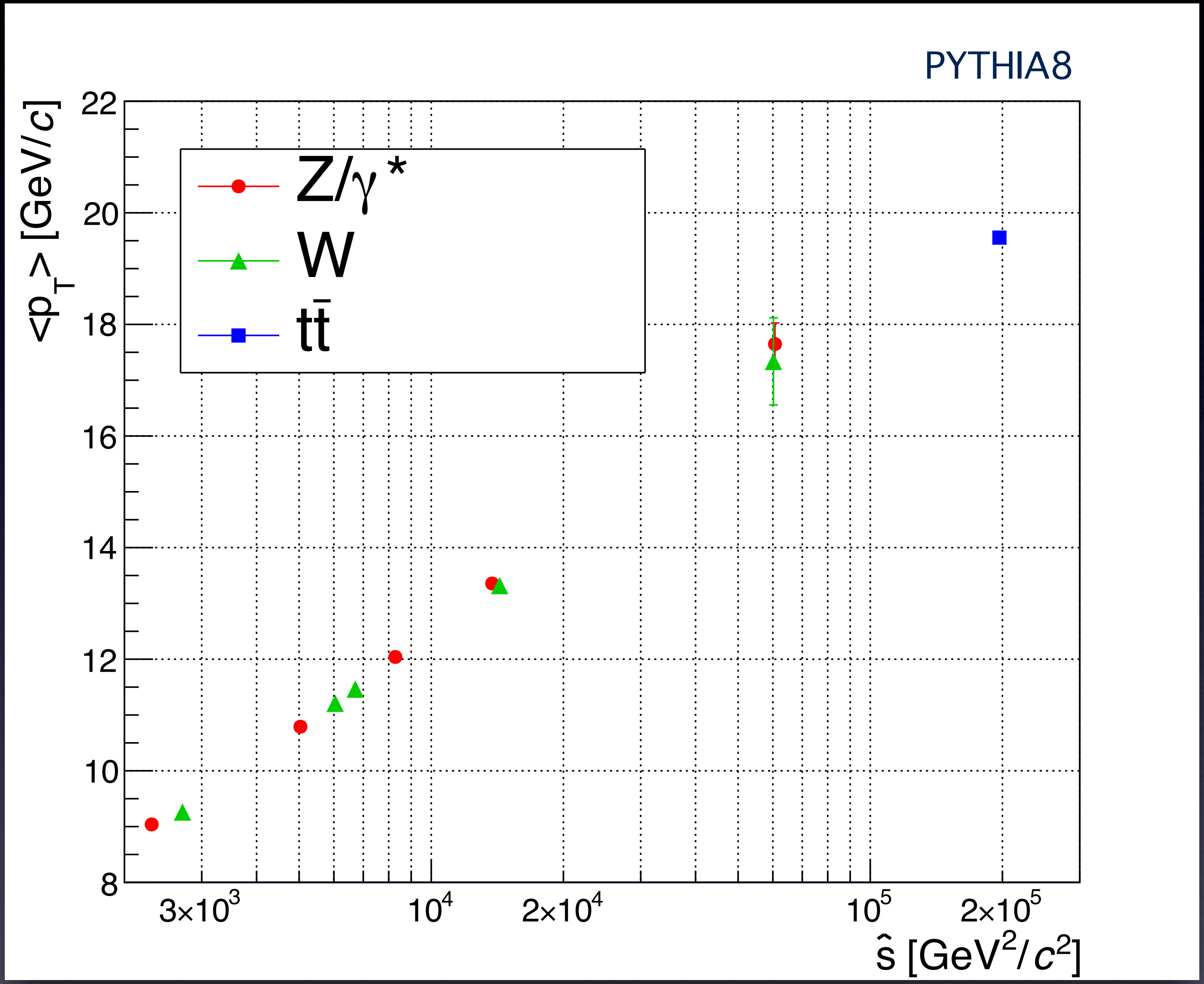
Mass bin	$\langle m_{DY}\rangle$±stat.±syst.	$\langle p_T\rangle$±stat.±syst.
[40,60]	47.72±0.05±0.04	9.12±0.09±0.12
[60,80]	70.66±0.04±0.07	10.81±0.08±0.14
[80,100]	90.99±0.01±0.08	11.84±0.03±0.03
[100,200]	115.29±0.18±0.14	13.17±0.12±0.12
[200,350]	243.33±1.63±0.41	16.18±0.61±0.46

ee channel

(GeV)

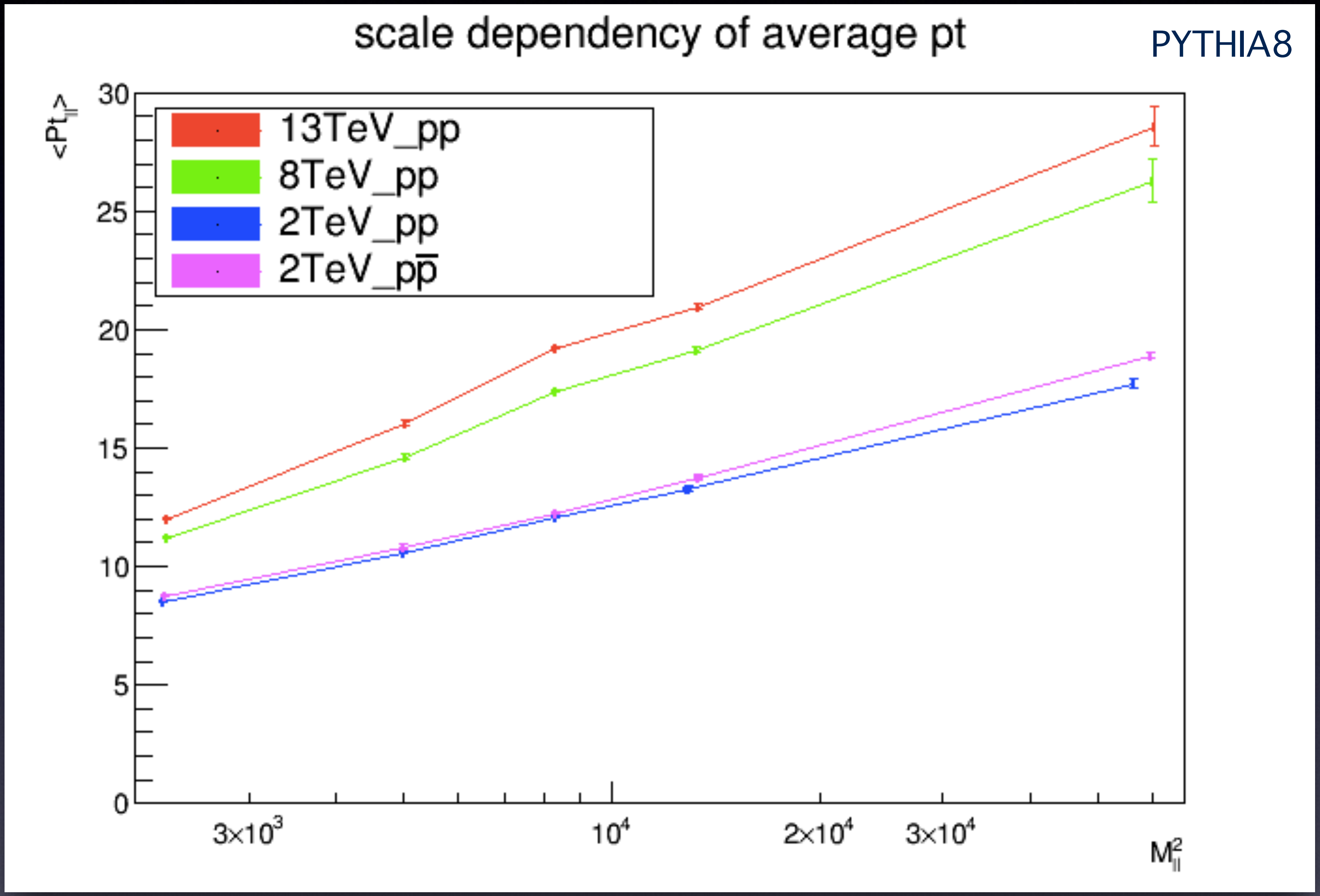
Mass bin	$\langle m_{DY}\rangle$±stat.±syst.	$\langle p_T\rangle$±stat.±syst.
[40,60]	47.83±0.05±0.07	9.10±0.13±0.18
[60,80]	70.76±0.04±0.04	10.84±0.08±0.10
[80,100]	90.98±0.01±0.07	11.79±0.02±0.02
[100,200]	115.11±0.13±0.14	12.93±0.09±0.08
[200,350]	245.46±1.29±0.36	16.41±0.56±0.27

Universality



Physics processes lie on the ISR slope in $<p_T>$ vs. $<Q^2>$

ISR activities projection



- Expected ISR activities does show slope changes by the collision energy

Summary

- QCD ISR is a process that is well-known but hard to study in hadron colliders although it is one of major systematic uncertainties in precision measurement

- Using Drell-Yan events in 9.4 fb^{-1} of CDF data, we measure the amount of ISR as p_T^{DY} depending on the Q^2, m_{DY}^2, and obtain a linear relation:

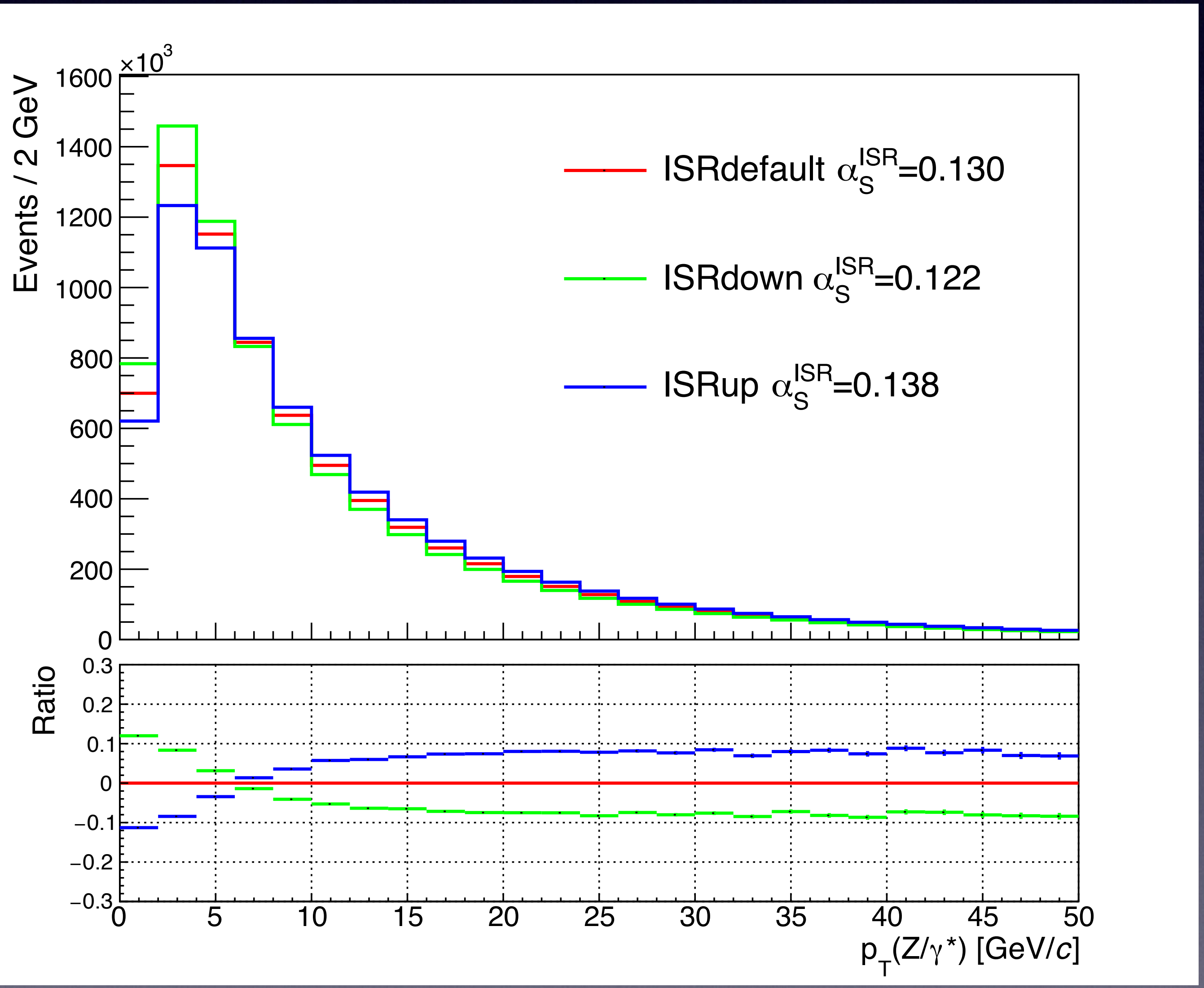
  - $p_T^{DY} = (-7.6 \pm 0.7) + (2.2 \mp 0.8) \times \log(m_{DY}^2)$

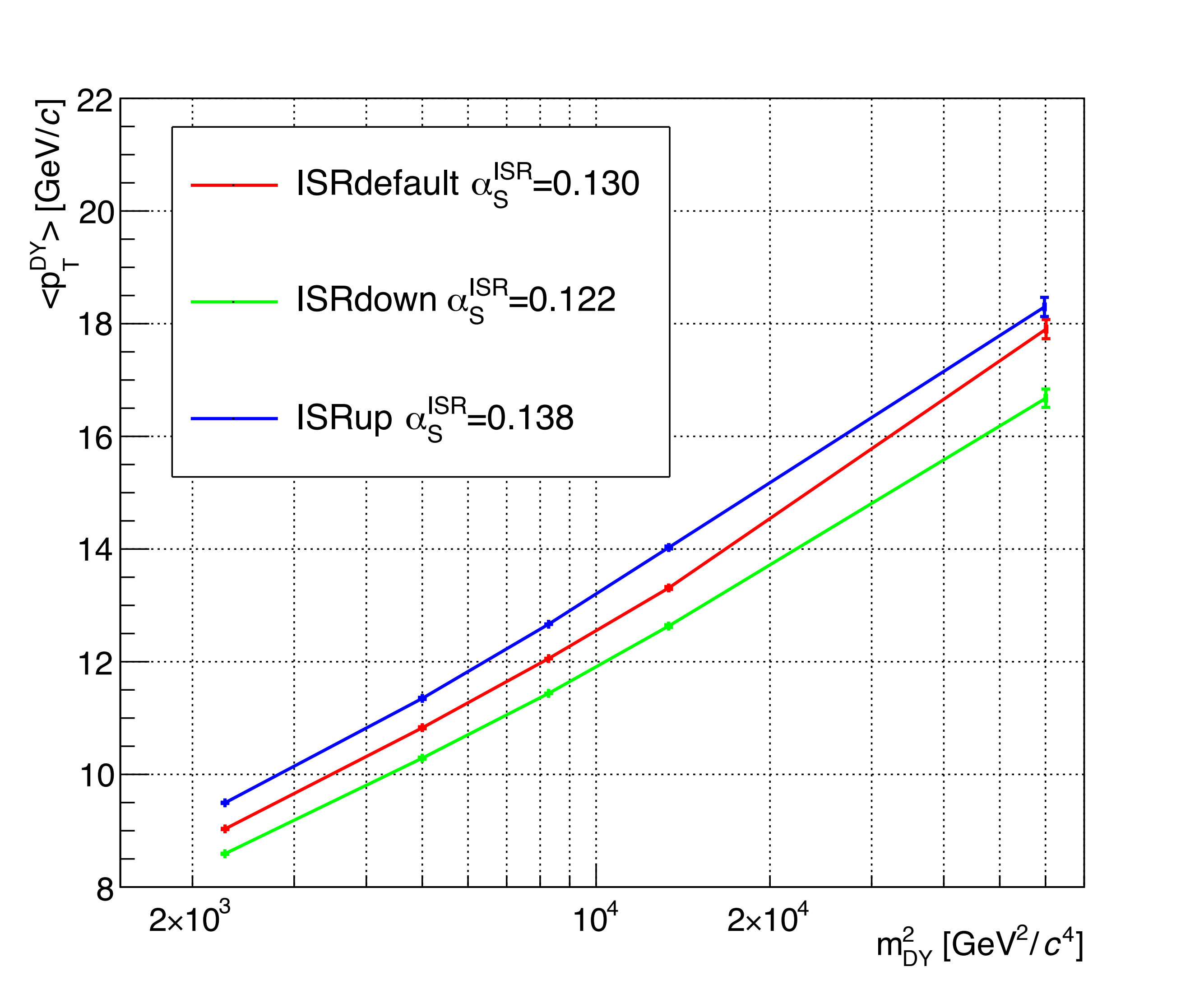
- This measurement gives an idea of estimating the p_T shifts induced by the ISR at high energy

- In preparation of paper submission

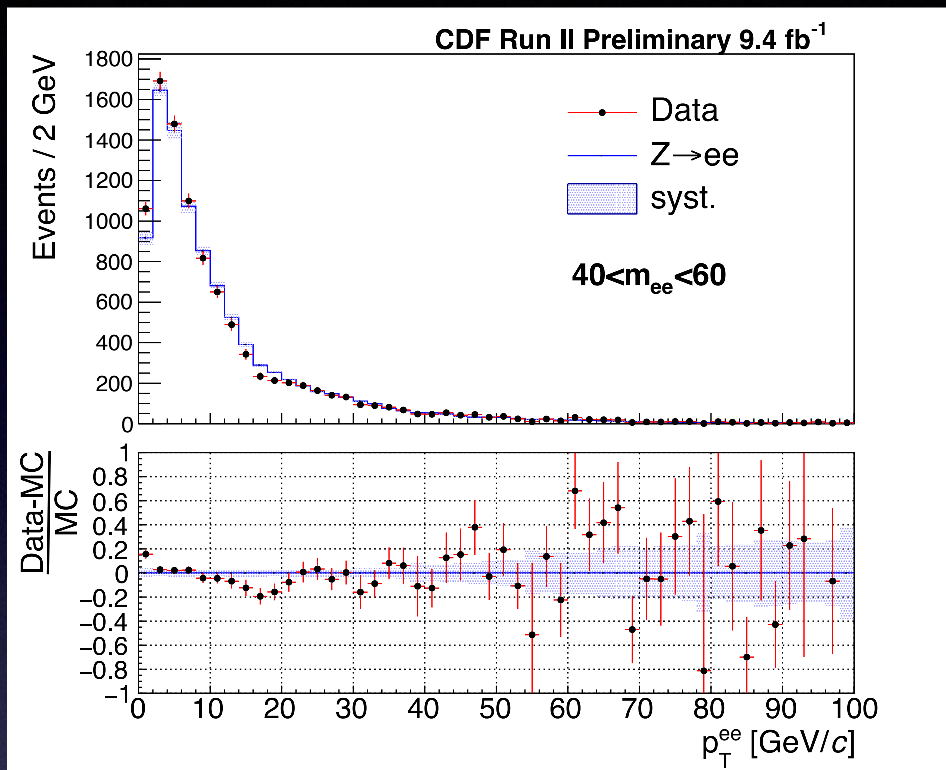
Backups

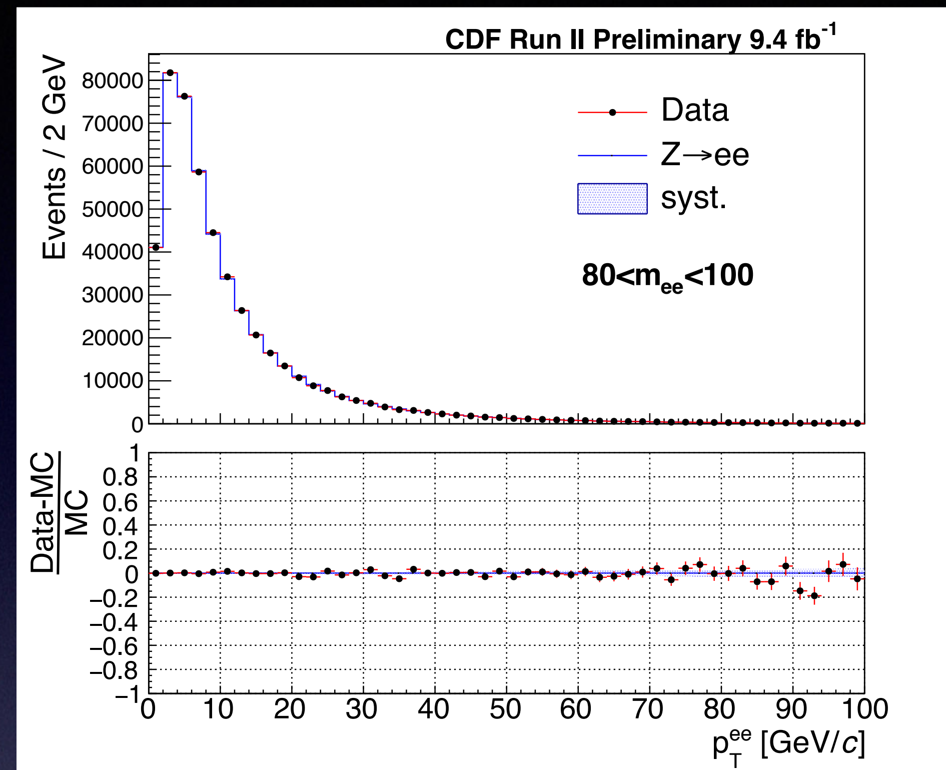
The measurement sensitive to α_S





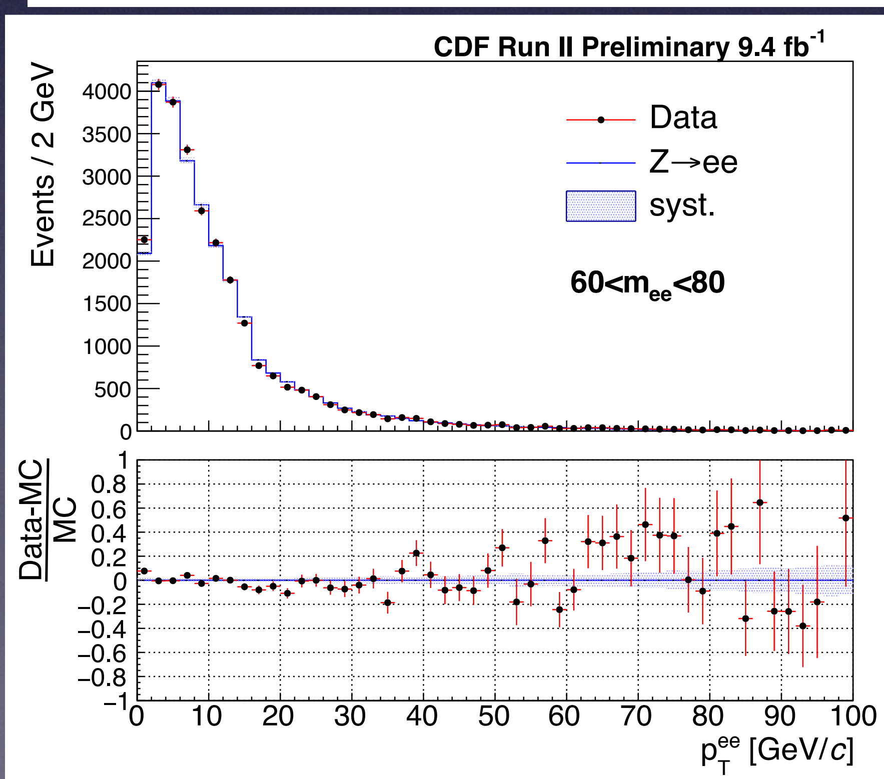
DiLepton p_T

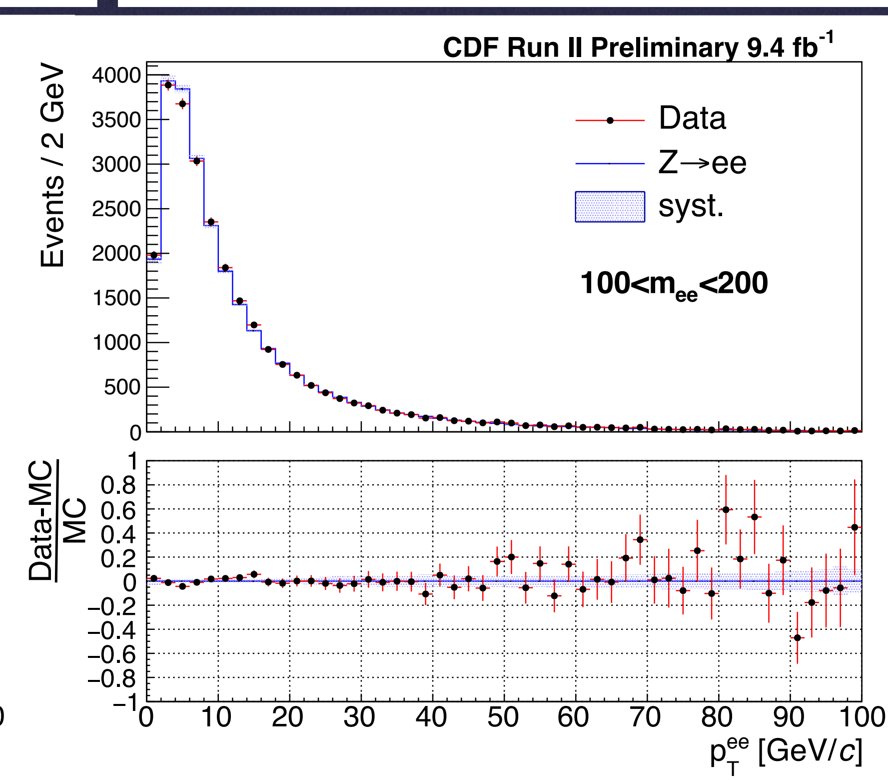


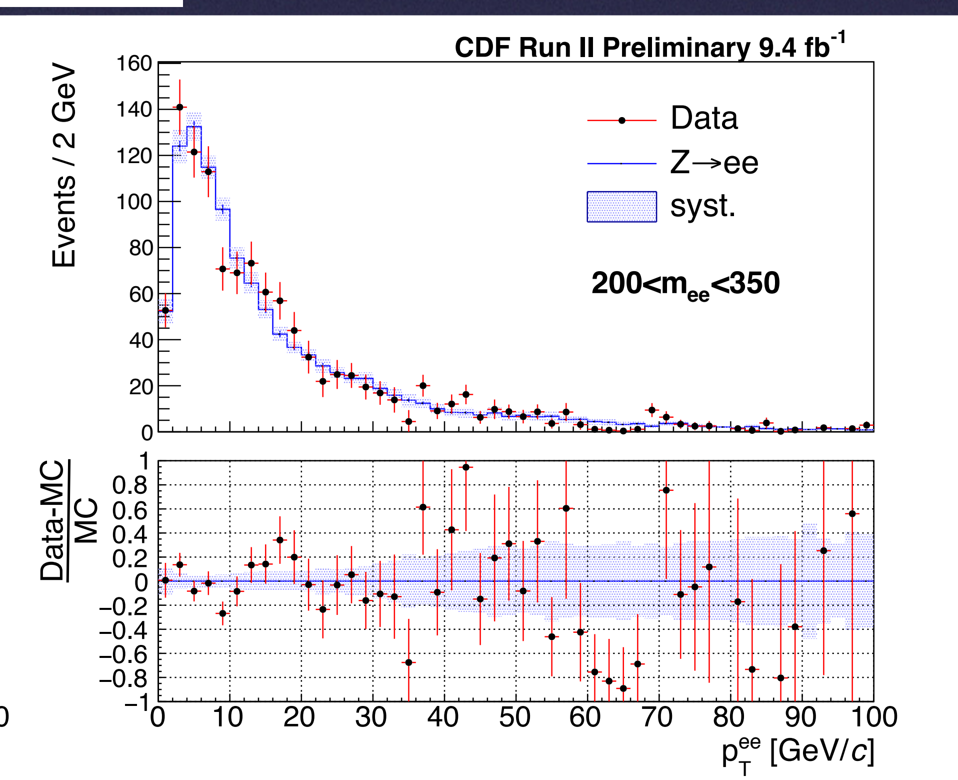


ee channel

Other SM backgrounds subtracted from Data

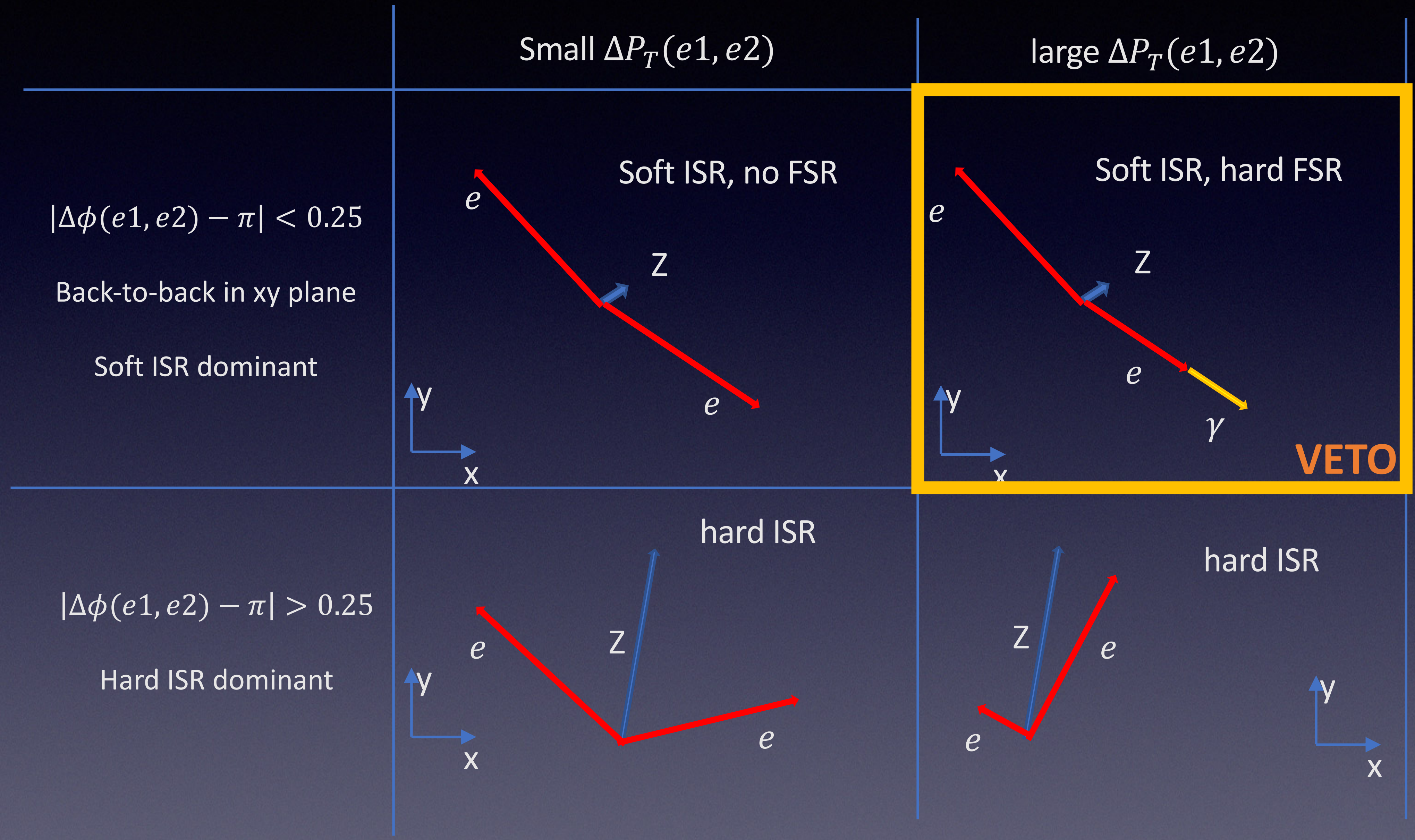






FSR-suppression cut

$\Delta p_T(e1,e2) \equiv |p_T(e1)-p_T(e2)|$, $\Delta\varphi(e1,e2) \equiv |\varphi(e1)-\varphi(e2)|$



For m_{ee}<80 GeV:

- $|\Delta\varphi(e1,e2)-\pi|<0.25$ && $\Delta p_T(e1,e2)>15$ GeV && MET<15 GeV
- $|\Delta\varphi(e1,e2)-\pi|<0.25$ && $\Delta p_T(e1,e2)>10$ GeV && MET>15 GeV

Boson p_T correction

- No reason that the pT correction differs by the lepton flavor
- We fully correct the detector acceptance to the generator level
  - Different acceptance in each channel
  - Correction differs by the boson rapidity
- Extracted the boson p_T correction iteratively from MC to data comparison using both lepton channels in 2D
  - $weight(p_T, y) = f_1(p_T) + y \times f_2(p_T)$

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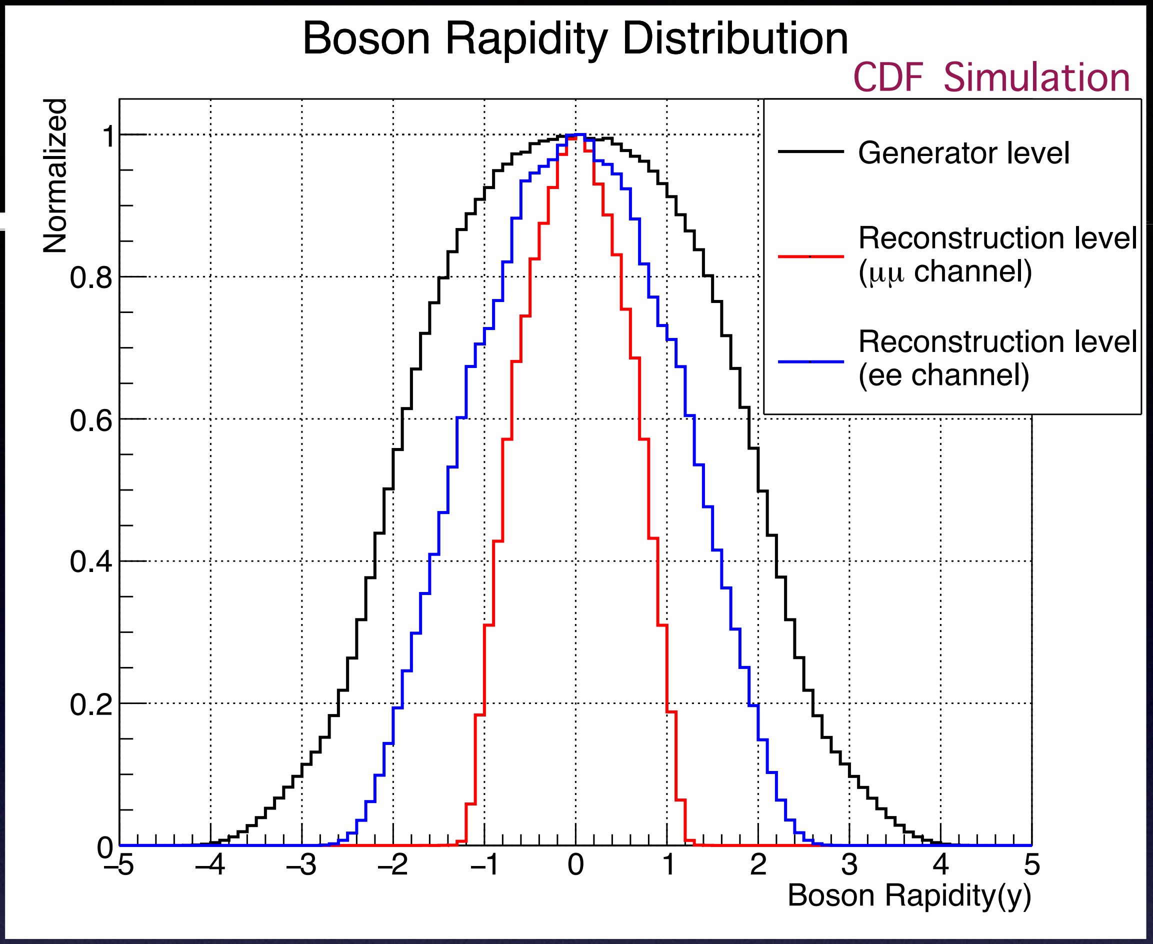

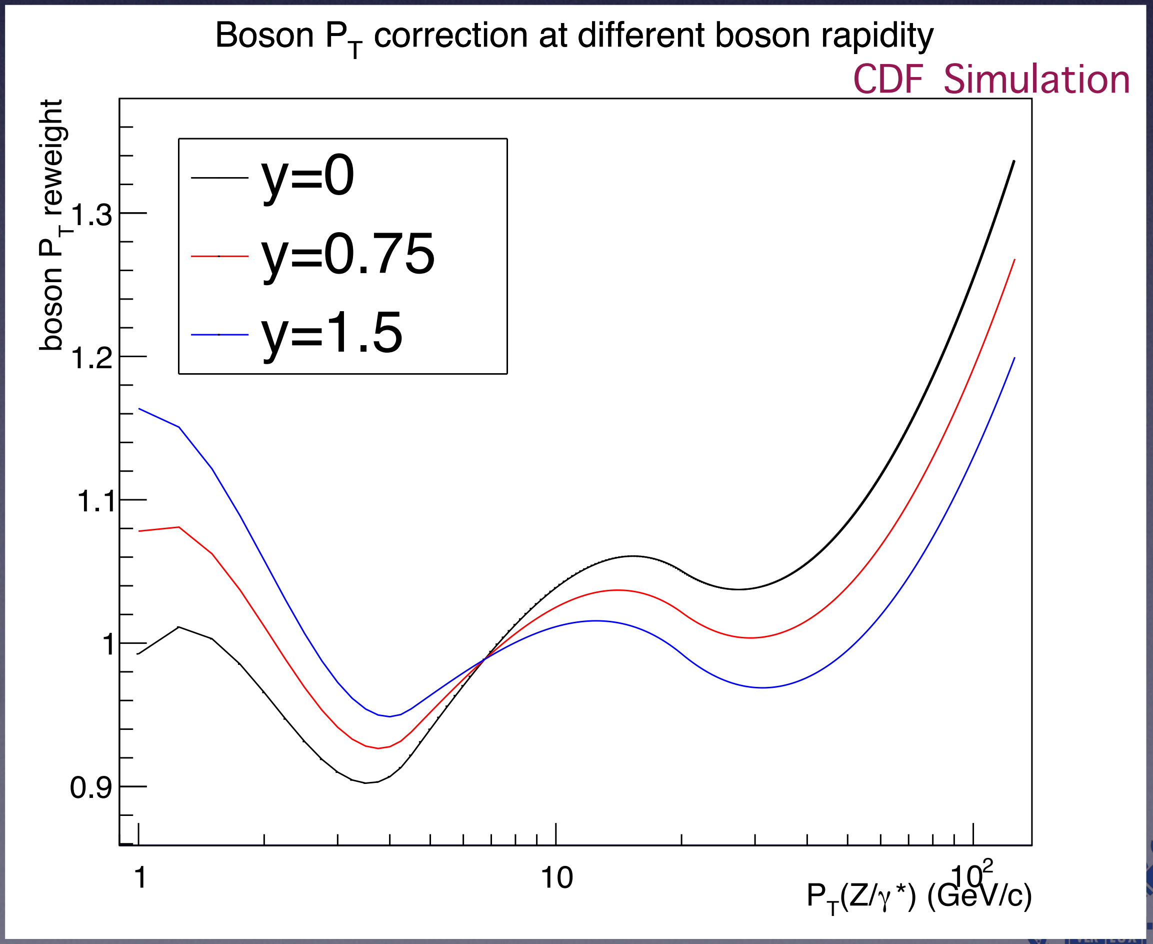

CDF detector details