Detector issues for future circular colliders

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Outline

Introduction – Snowmass studies and framework

Detectors for future hadron collider – 100 TeV

- Tracker
- Calorimetry
- Muon detector
- Performance studies

Detectors for lepton collider

- Physics goals
- Detector choices
- Parameterized framework

Summary and Conclusion

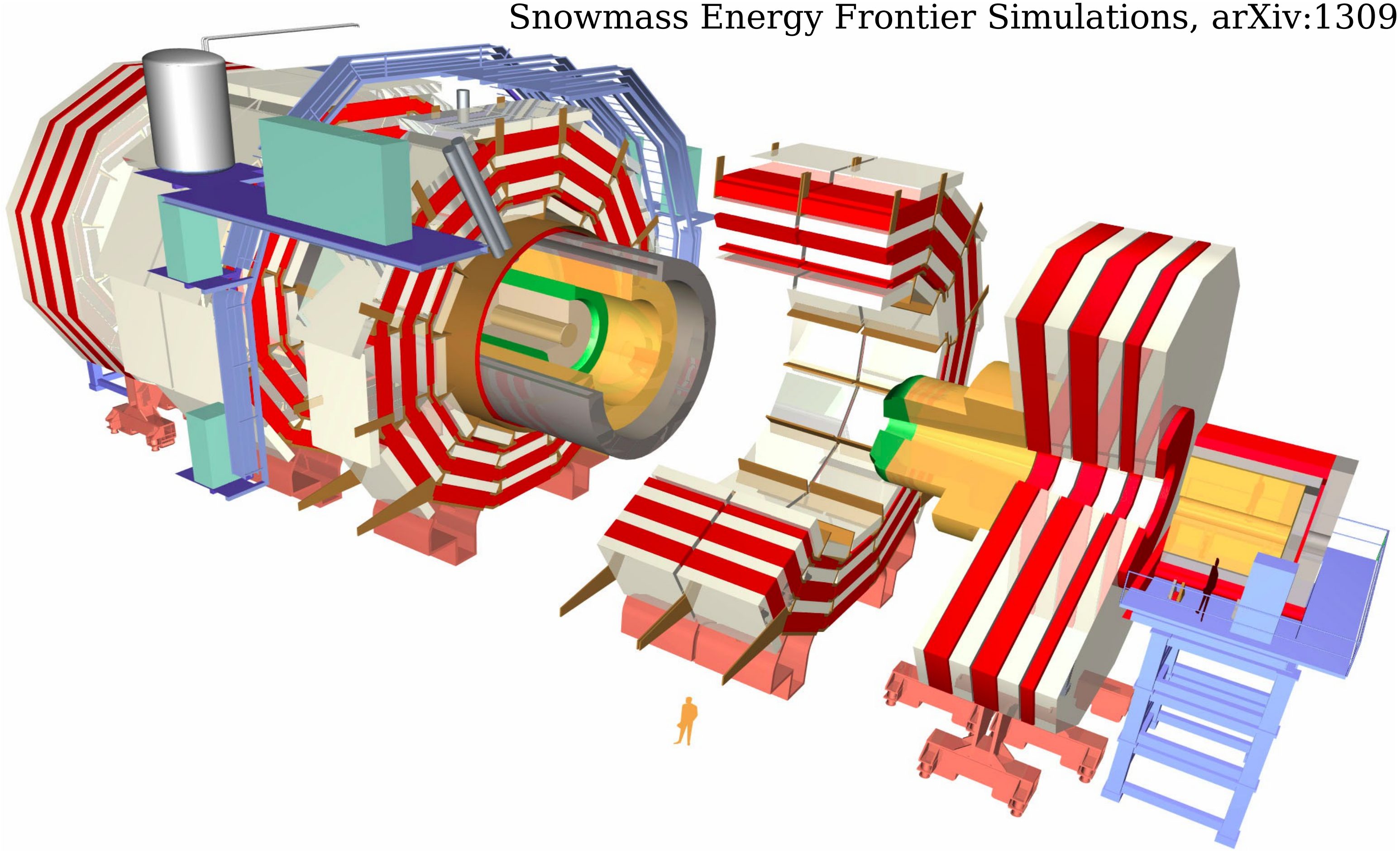
Snowmass Studies

For long range physics planning at Snowmass, we wanted to make a physics case

- with high luminosity running, higher energy, etc.

It was decided to use parameterized detector, called Snowmass Combined LHC detector

Snowmass Energy Frontier Simulations, arXiv:1309.1057, Sept. 2013



"Components" from the ATLAS and CMS detectors:

- CMS tracker
- ATLAS Calorimeter
- CMS B-Field, etc

Responsible for co-leading the Snowmass Technical Advisory Board (Detector and Instrumentation)

- parameterized detector was used in almost all snowmass papers/studies

Simulation framework for Snowmass

Delphes-3 fast simulation (https://cp3.irmp.ucl.ac.be/projects/delphes)

- It supports addition of PU events
- Many improvements were motivated based on current studies

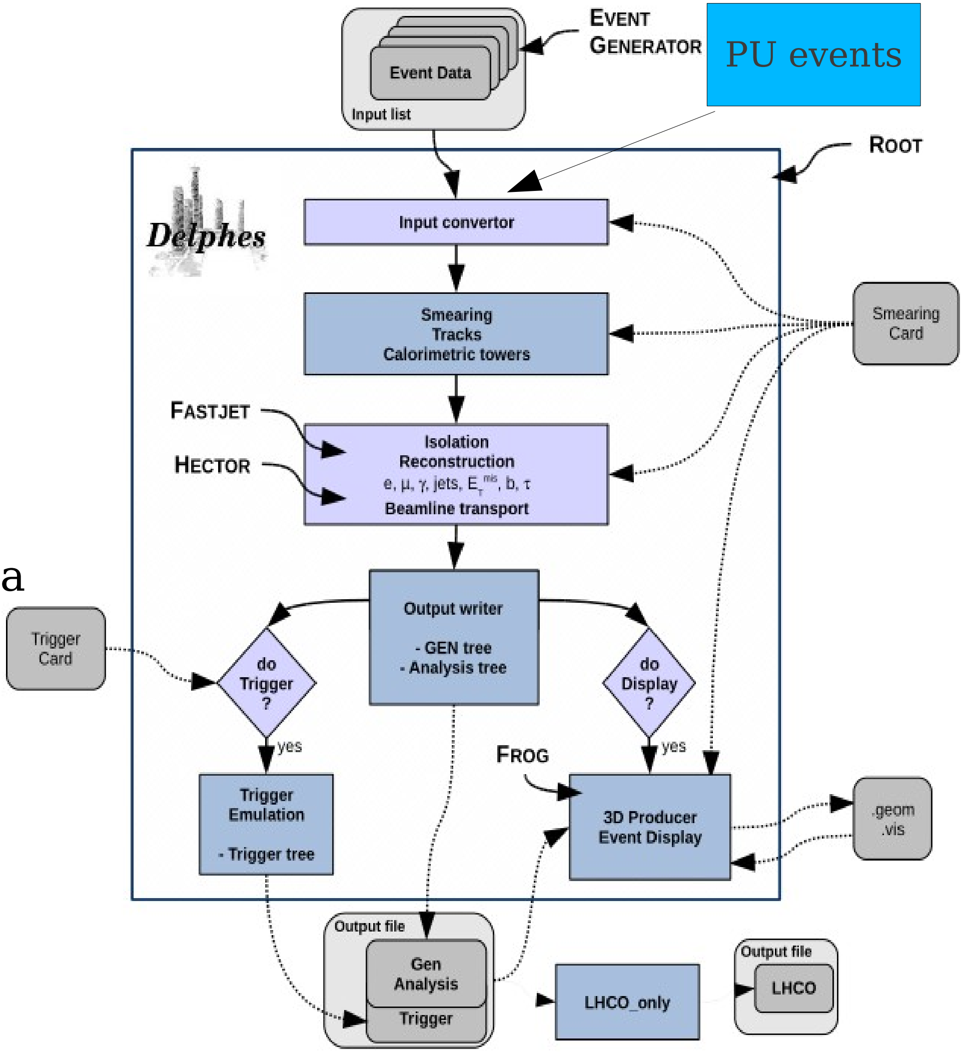
For Phase-I studies:

We used Delphes3 framework with:

- realistic detector performance with PU =50
- parameterize using available full simulation
- retain object performance as obtained using data
- use best of both ATLAS/CMS performance (if publicly available)

For Phase-II studies:

- use higher pileups – 140
- assume the upgraded detector with best available performance
- use best of both ATLAS/CMS expected performance
- pileup subtraction was be the key



Key assumptions

The performance studies were based on general understanding of current detectors

Pile-ups (PUs) are extracted using Minbias events with Z2* tune (CMS Tune)

Pile-up subtraction was the key

(with publicly available parameters from the experiments)

- Charged particles are subtracted at the mixing level

- Similar to vetoing “Charged tracks” NOT coming from the primary vertex.

- Neutral particles are subtracted based on fastjet area method (ρ method)

- In the endcap/fcal (outside the tracker acceptance) ρ method is used

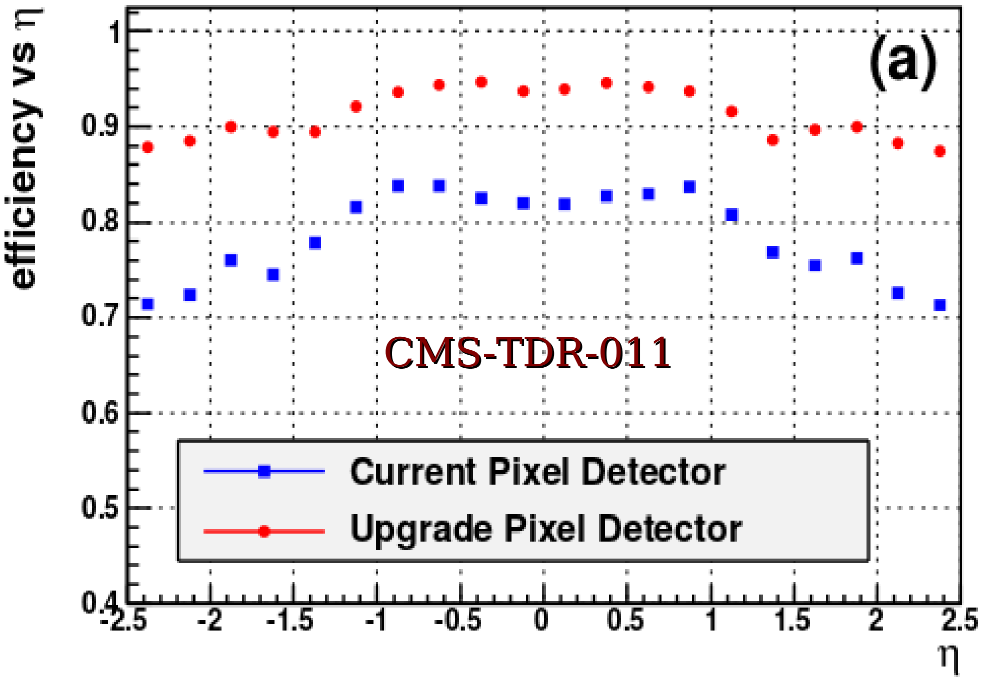
The Z vertex spread in the beam direction, assuming gaussian - 5 cm

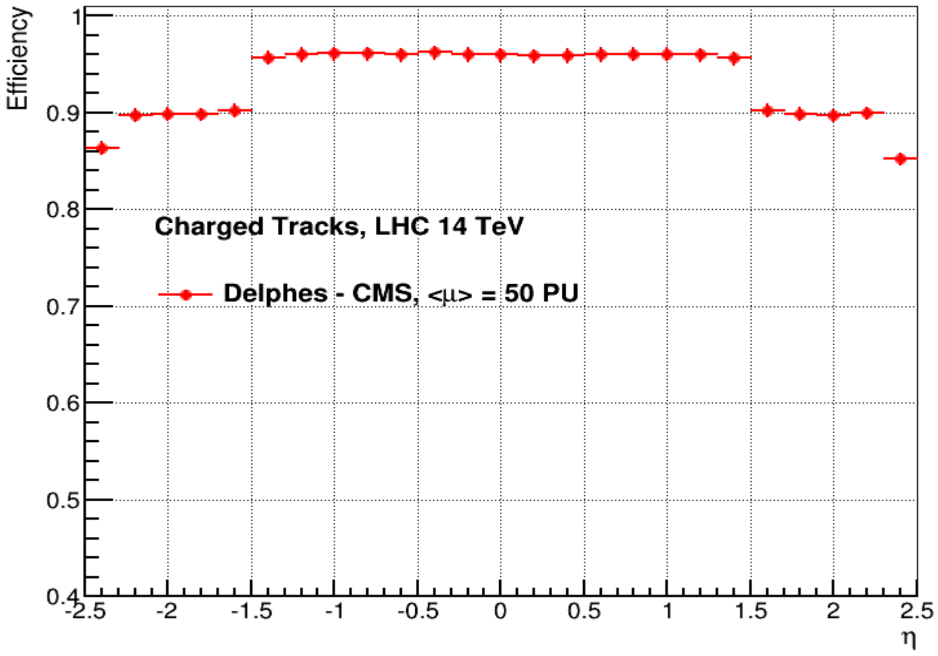
The resolution spread in the Z vertex direction – 0.1 cm

Magnetic Field = 3.8 Tesla

Radius of magnetic field coverage = 1.2 m

Tracking performance and expectation for Snowmass





Sample and Conditions		Tracking Efficiency (%)		Track Fake Rate (%)	
Sample	PU/DL/Cuts	Current	Upgrade	Current	Upgrade
Muon	0/No/Cleanup	97.4	98.1	0.0	0.0
Muon	0/Yes/Cleanup	93.9	97.9	0.0	0.0
Muon	50/No/Cleanup	90.1	94.9	0.22	0.17
Muon	50/Yes/Cleanup	81.5	94.4	0.23	0.17

Object reconstruction and algorithms - Particle Flow

Particle propagation:

Neutral: trajectory is a straight line from production point to the calo cell

Charged: Follow helicoidal trajectory until it reaches the calorimeter

Calorimeter:

- Finite segmentation in eta and phi: determines cell size
- Segmentation is uniform in the transverse direction
- Towers are computed using geometrical center of the cell

Tower energy:
$$E_{Tower} = \sum_{particles} \ln\mathcal{N}\left(f_{ECAL} \cdot E, \sigma_{ECAL}(E,\eta)\right) + \ln\mathcal{N}\left(f_{HCAL} \cdot E, \sigma_{HCAL}(E,\eta)\right).$$

Particle Flow: If the momentum resolution of the tracking system is higher than the energy resolution of calorimeters, it can be convenient to use the tracking information within the tracker acceptance for the charged particles momenta

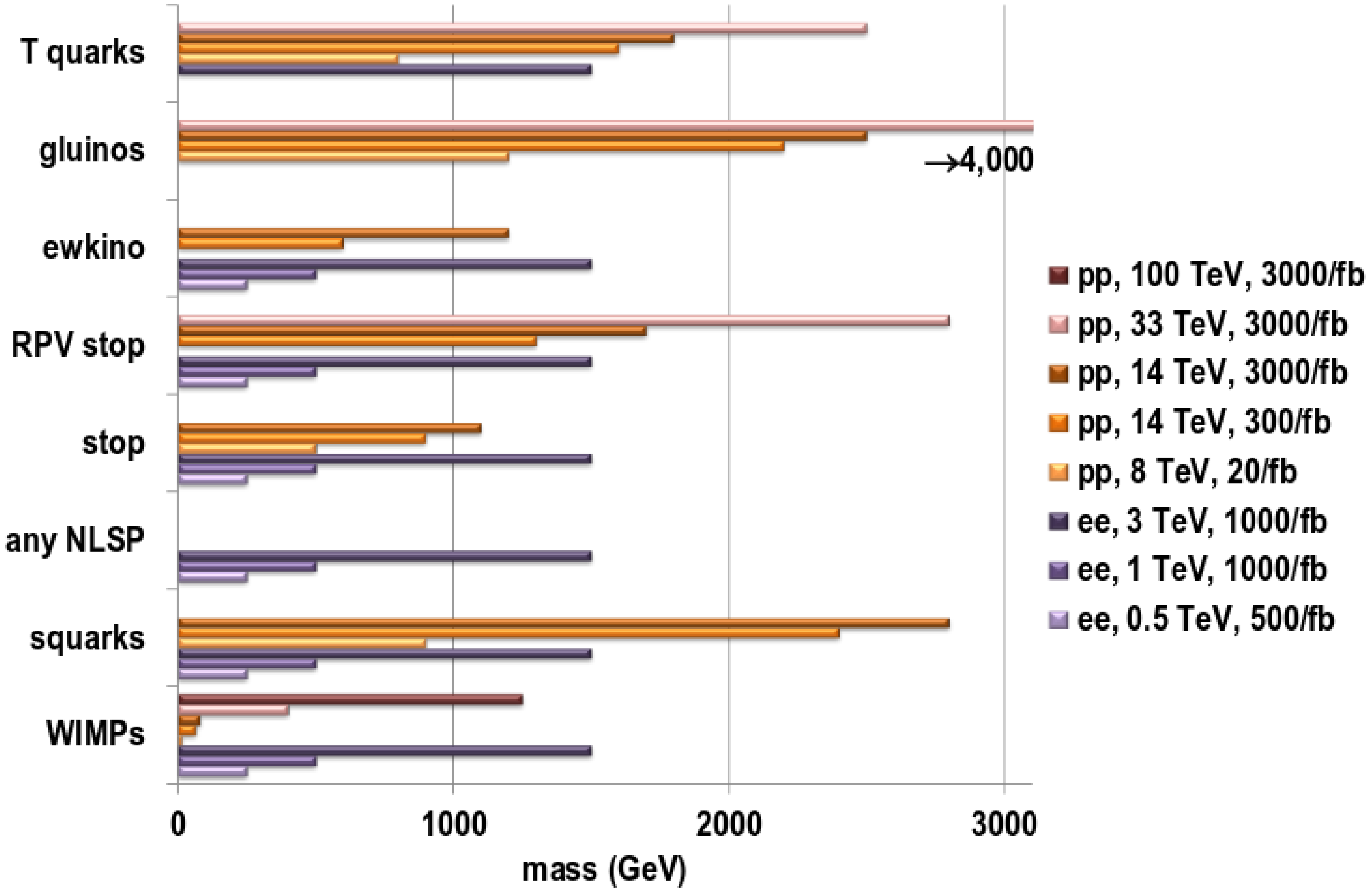
- Ncalo: the total number of hits that originate from all long-lived particles
- Ntrk: the number of hits that originate from a reconstructed track

If Ncalo = Ntrk; Momentum resolution of tracks are used

If Ncalo > Ntrk: Produce particle flow tower also using ECAL and HCAL info.

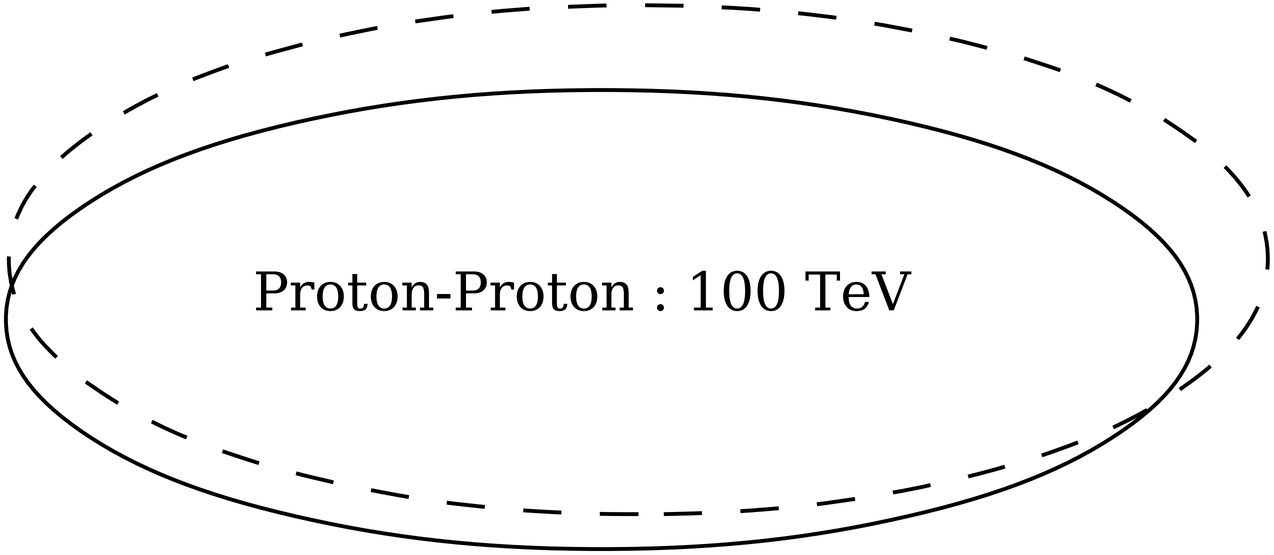
Mixed case: Subtraction of charged particle energy to determine neutral deposits

Snowmass results



Current expectations for future facilities around the globe

Circular pp Collider - Detectors



Proton-Proton : 100 TeV

Hadron Collider detector requirement

Additional interactions with pp collisions - Pileups

$$< N_{\text{pileup}} >= \frac{\sigma_{\text{inel}}}{(1\ \text{b})} \times \frac{L}{(10^{33}\ \text{cm}^{-2}\text{s}^{-1})} \times \frac{\tau_b}{(1\ \text{ns})}$$

$$\sqrt{s} = 100\ TeV, \sigma_{inel} = 105\ mb, L = 5 \times 10^{34}, \tau_b = 25, < N_p >= 131 \approx 140$$

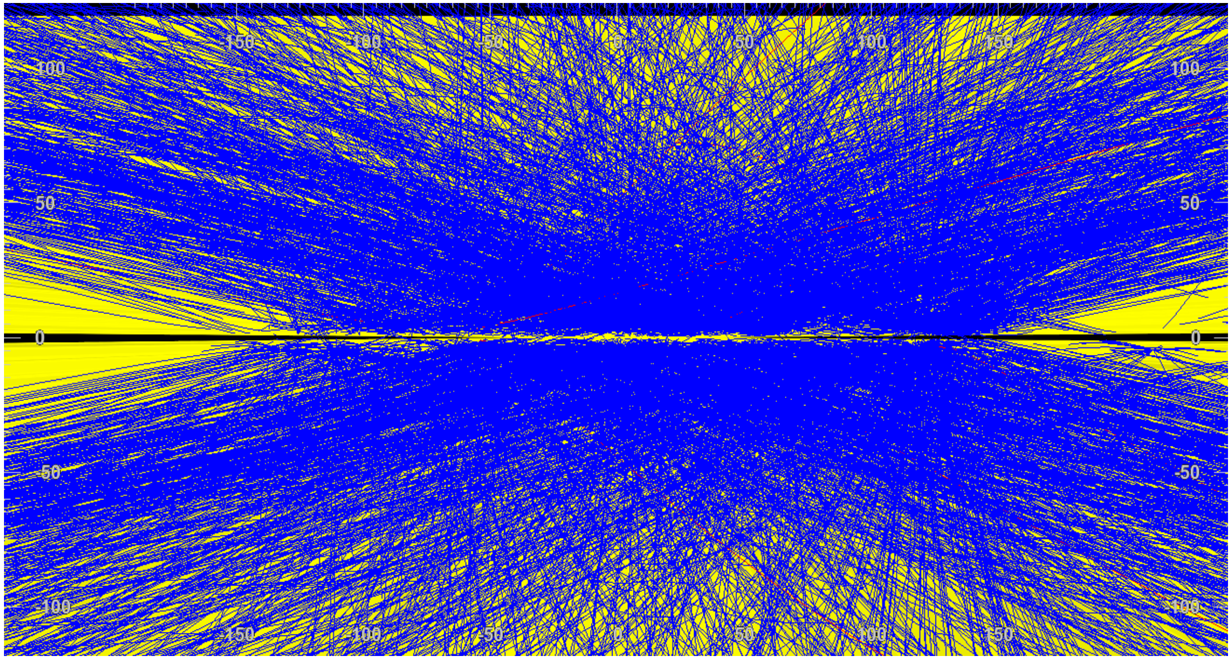
$$\sqrt{s} = 100\ TeV, \sigma_{inel} = 105\ mb, L = 2 \times 10^{34}, \tau_b = 19, < N_p >= 39.9 \approx 40$$

[Assumed for VLHC, FNAL]

$$\sqrt{s} = 100\ TeV, \sigma_{inel} = 105\ mb, L = \boxed{10} \times 10^{34}, \tau_b = 5, < N_p > \approx 53$$

[Assumed for FCC, CERN]

$$Z \to \nu\nu + 140PU@100\ TeV$$



Snowmass Detector – 100 TeV

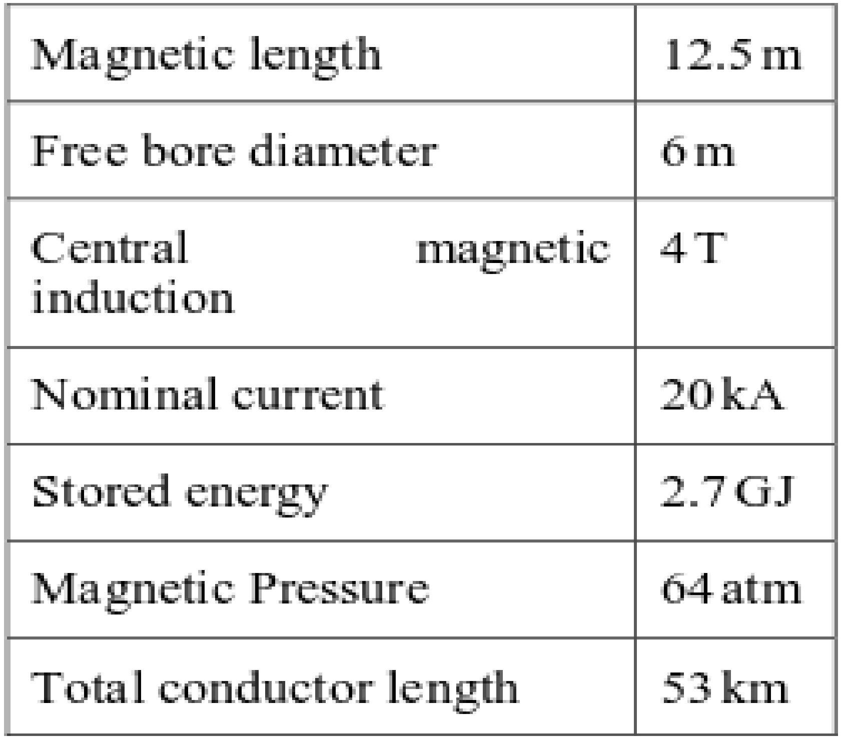
(140 Pileup, 3.8 T field)

14 TeV LHC with 140 PU is not the same as 100 TeV machine with 140 PUs.

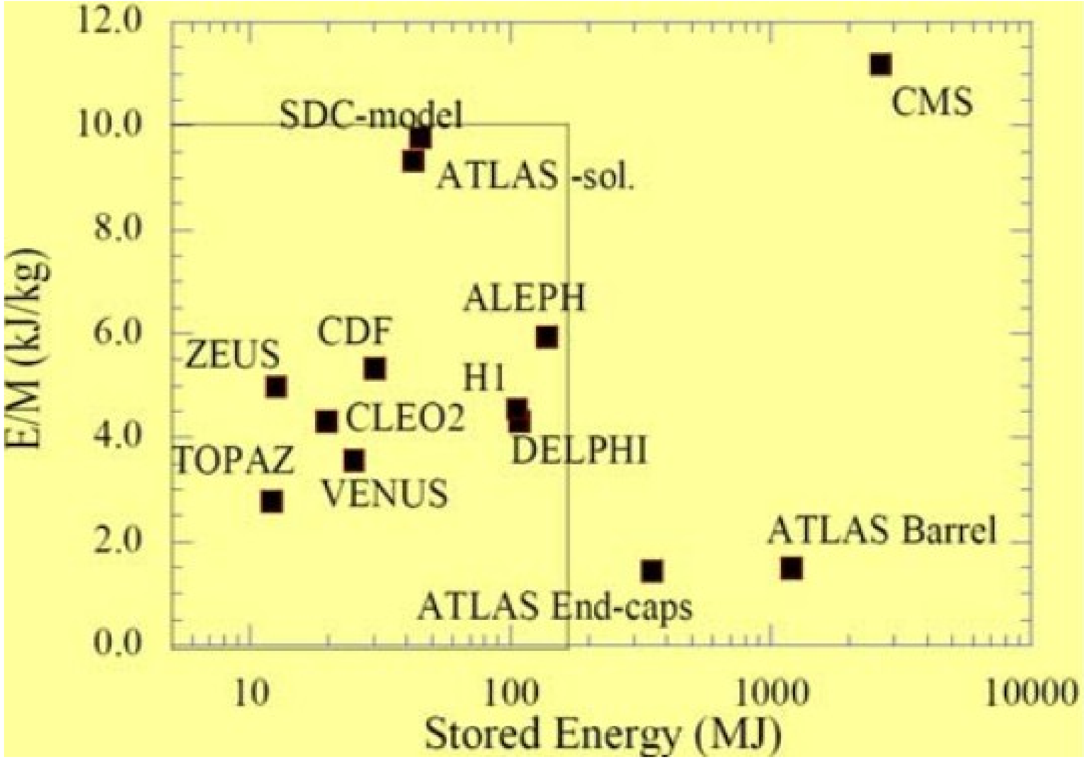
Large magnetic field will help

Hadron Collider detector – Magnetic Field

Latest technology in HEP - Superconducting magnets from CMS



Magnetic length	12.5 m
Free bore diameter	6 m
Central magnetic induction	4 T
Nominal current	20 kA
Stored energy	2.7 GJ
Magnetic Pressure	64 atm
Total conductor length	53 km



ILC (SiD) proposed to use “similar technology” up to <u>5 T field</u>

- upper bound at which such a large aluminium stabiliser/structure magnet can be operated in a fail safe manner

100 TeV detector (large field): Increases central bending power for muons ~1 TeV

Based on absorber choice, can accommodate the large absorbing length > 12λ

For this study use magnetic field of 5T (baseline)

Hadron Collider detector – Tracker

Next generation tracker will require:

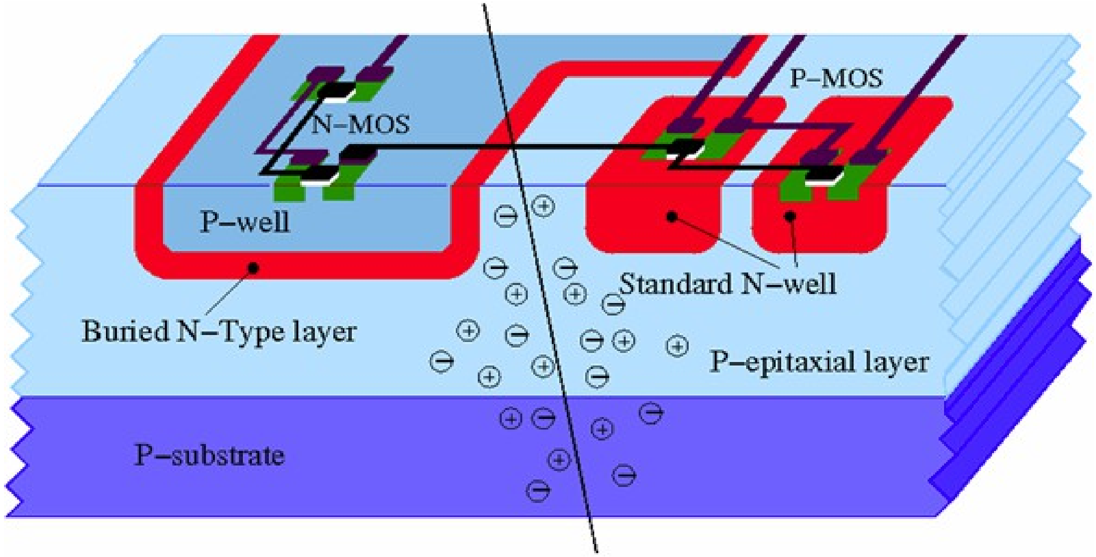
- High resolution in high rate environment (thin, highly pixelated sensors)
- Time measurement (for pileup reduction)
    - thin, low capacitance sensors
- radiation hard (dose of 2 x 10^{16} neq/cm^2; neq/cm^2 is 1MeV neutron fluence)
    - operate at low temperature (-20° C to reduce leakage current)
    - reduce depletion depth
- Low mass (thin sensor ~300 μm thickness)

Monolithic active pixel sensors

Low resistivity silicon wafer is used as a sensitive detector, the charge librated is collected by diffusion.

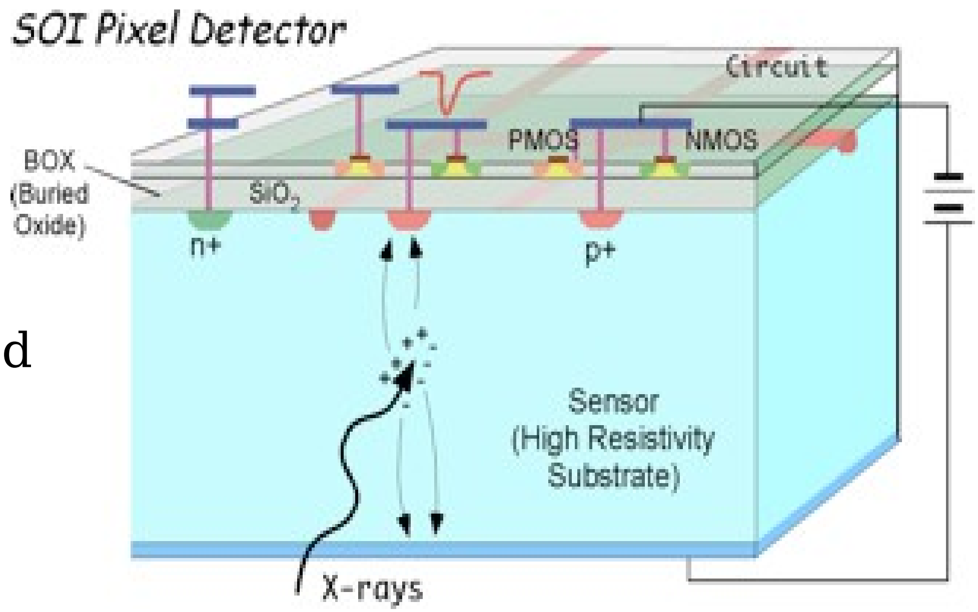
- Sensor is a photodiode with a special structure to allow high detection efficiciency

Issues: Radiation hardness, slow, etc



Hadron Collider detector – Tracker

Silicon on insulator sensors (SOI)

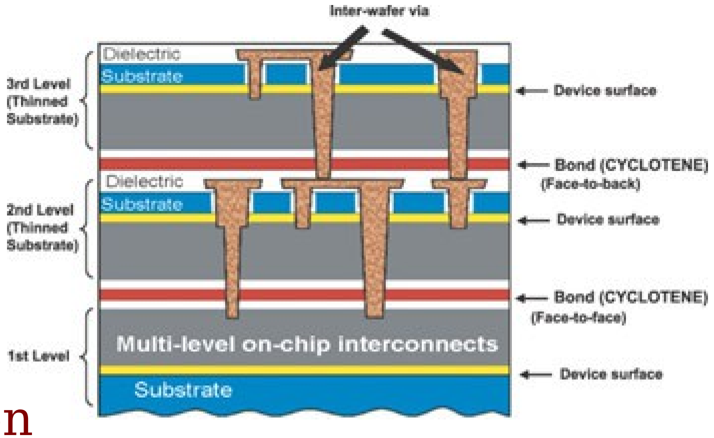


In SOI, the sensor and the readout electronics are bonded on a single chip. For the electronics to be connected to the detector, integrated circuit technology called complementary metal-oxide semiconductor (CMOS) is used. The insulating layer is sub-micron in thickness separates the readout electronics part and its silicon substrate.

Advantage: Large, Fast signal, high granularity

Issues: Radiation hardness, coupling of digital electronics and sensor

3D pixel Integration



- vertical stacking of wafers by vias, bonding, thinning, interconnection

Advantage: Same as above

Issues: Availability of technology, large scale production

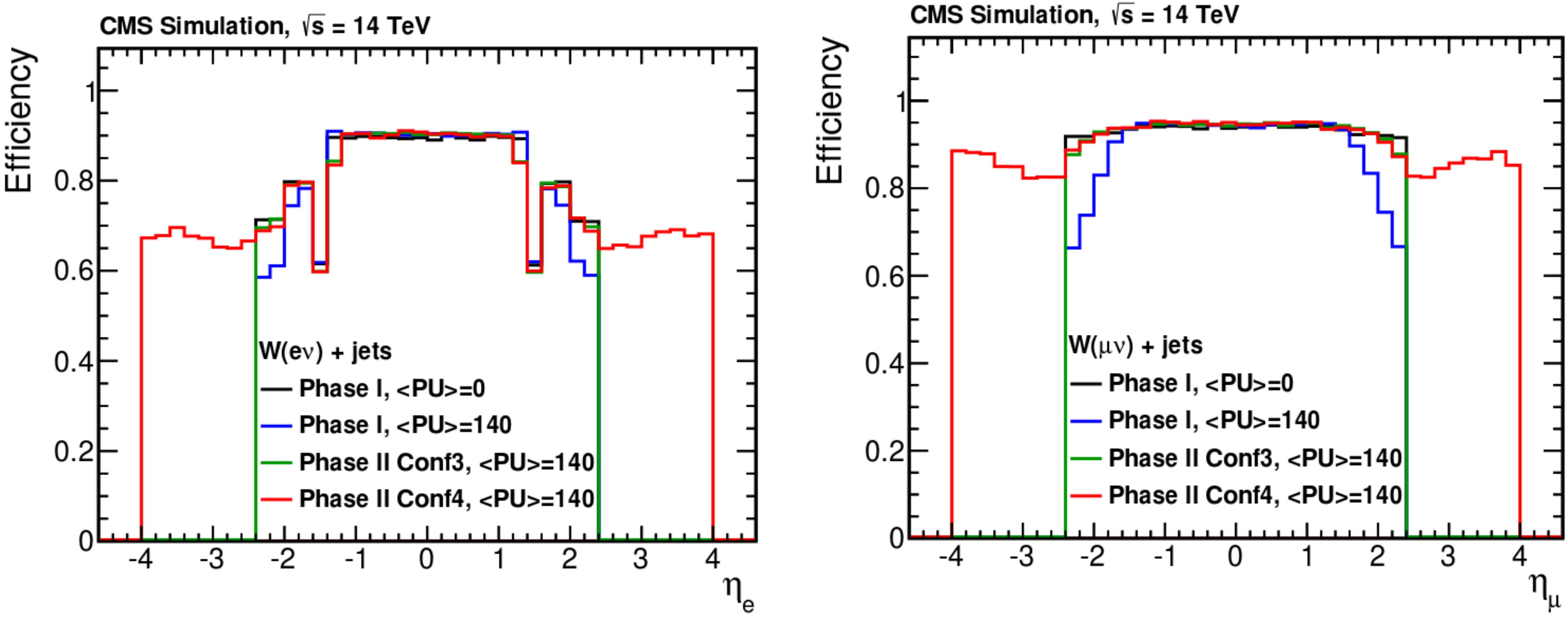
Hadron Collider detector – Tracker

There are other emerging technologies: 3D pixel sensors, diamond sensors, etc

See more details: 100 TeV workshop talk by U. Heintz, arXiv:1401.6116v1

For this study we will use: HL-LHC silicon based upgraded detector

- CMS ECFA Phase-II studies uses similar parametrization (as Snowmass detector)
- Pseudorapidity extended up to |η| ~ 4.
- Large gain in lepton acceptance even with 140 PU



Hadron Collider detector – Calorimetry

ECAL needs to have “low energy leakage” as well as good segmentation

For ~ 0.1% leakage, the thickness of EM part ~ 30 radiation length

CMS Crystal (lead tungstate, PbWO4) : 25 X_0, ATLAS LAr (segmented) 23-29 X_0

1. Electromagnetic Calorimeters

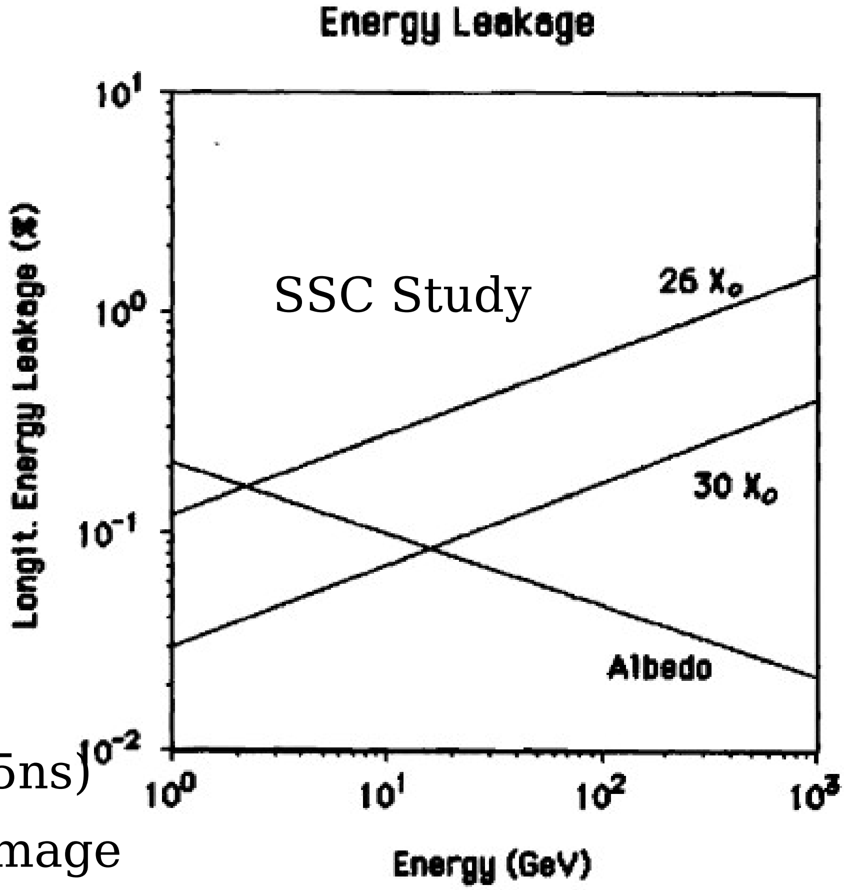
SSC Study

E (GeV)	1%/√E	10%/√E	20%/√E
1	1%	10%	20%
10	0.3	3	6
50	0.14	1.4	3
100	0.1	1	2
500	0.04	0.4	0.9
1000	0.03	0.3	0.6

Constant term B

~2 to 3% in present detectors

Hope for ~1% at the SSC



Resolution is essential for leptonic Higgs studies

Speed of response is good using Crystals (25ns, 5ns)

- Issues with light output due to radiation damage

High segmentation is essential for Particle Flow

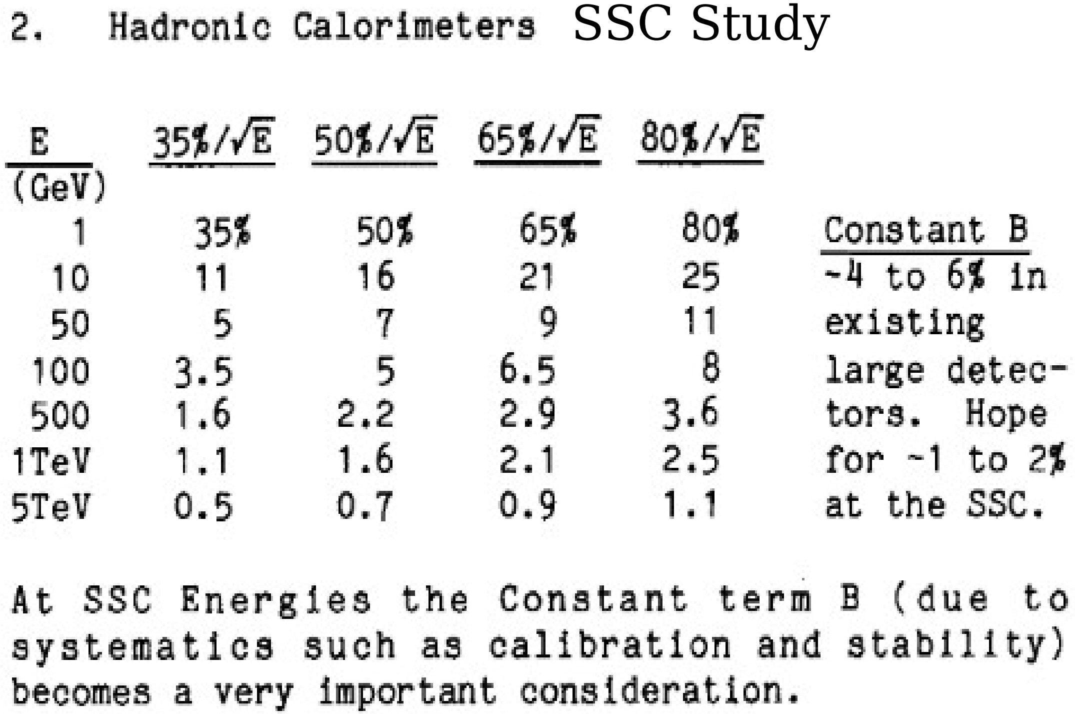
In this study we use (similar to CMS Crystal) $\sigma/E = 2.0\%/\sqrt{E} \oplus 0.5\%$

Hadron Collider detector – Calorimetry

With 100 TeV Collider, we expect jets up to ~ 50 TeV

- SSC studies shows for a 20 TeV Jet, several 1 TeV Hadrons are produced

Containment is extremely essential

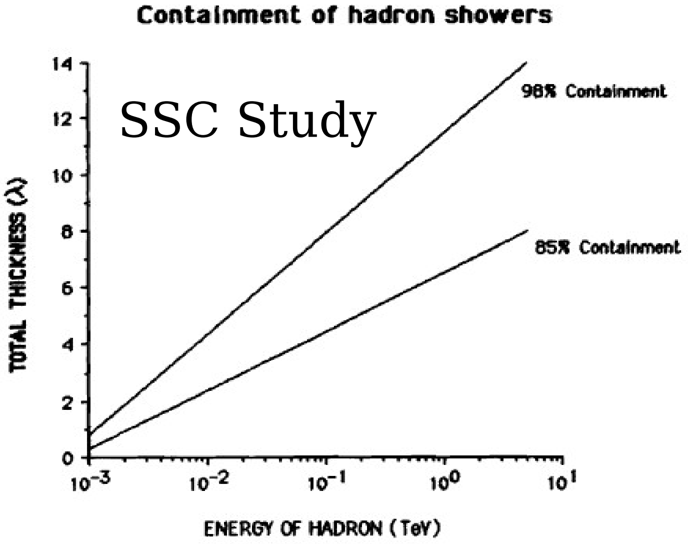


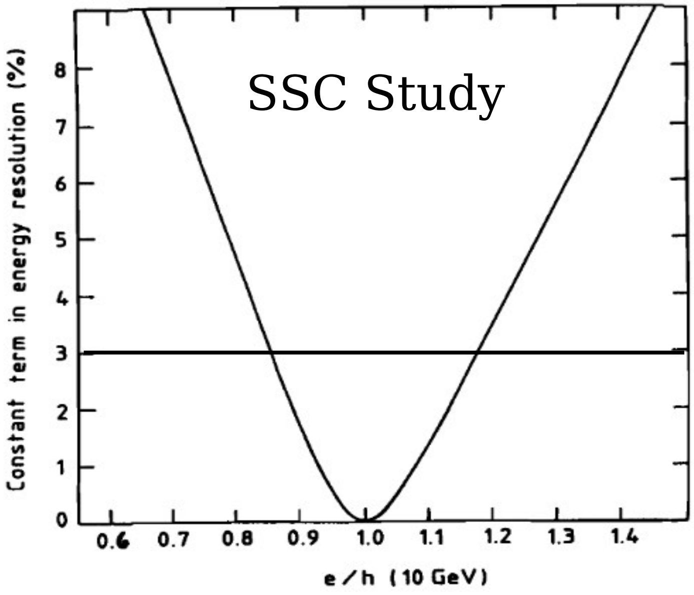
2. Hadronic Calorimeters SSC Study

E (GeV)	$35\%/\sqrt{E}$	$50\%/\sqrt{E}$	$65\%/\sqrt{E}$	$80\%/\sqrt{E}$
1	35%	50%	65%	80%
10	11	16	21	25
50	5	7	9	11
100	3.5	5	6.5	8
500	1.6	2.2	2.9	3.6
1TeV	1.1	1.6	2.1	2.5
5TeV	0.5	0.7	0.9	1.1

Constant B
~4 to 6% in
existing
large detec-
tors. Hope
for ~1 to 2%
at the SSC.

At SSC Energies the Constant term B (due to systematics such as calibration and stability) becomes a very important consideration.





Iron/Scintillator Calorimeter can be a good choice

However, constant terms to be < 3% e/h = 1 ± 0.15

In this study we use (ATLAS): $\sigma/E = 50\%/\sqrt{E} \oplus 3\%$

Hadron Collider detector – Calorimetry

Compensating Calorimeter such as ZEUS (uranium scintillator)

- same response for EM and hadronic component

- neutrons liberated in hadronic interactions can be slow for 25/5 ns crossing

Particle Flow Calorimeters

- **charged particles measured in tracker (essentially perfectly)**
- **Photons in ECAL:** $\sigma_E/E < 20\%/\sqrt{E(\mathrm{GeV})}$
- **Neutral hadrons (ONLY) in HCAL**
- **Only 10 % of jet energy from HCAL ⇨ much improved resolution**

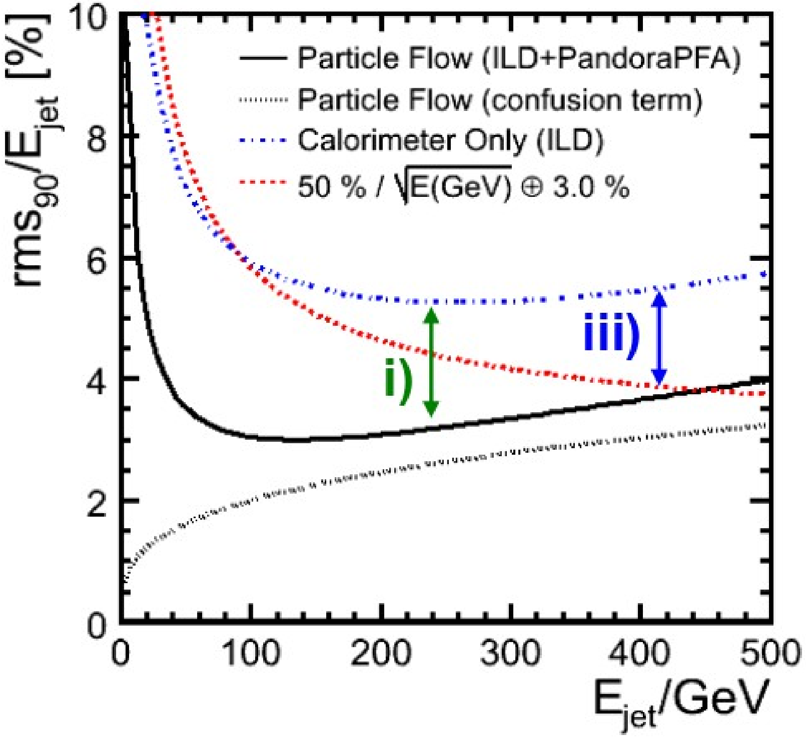
These are imaging calorimeter

- PF requires detailed image of shower

- high granularity detectors

- micro-pattern gas detectors

Planned for ILC for e^+e^- detector



Issues:

- Not clear if it can work at high rate

- Not good for the constant term

PS CMS Combined PF detector is planned for HL-LHC)

Hadron Collider detector – Muon detector

CMS Muon Chamber:

- It has 4 muons stations (MSX)
- Outside the magnetic Coil, with
  iron plates in between them.

It uses Drift Tube (Ar/CO$_2$) $|\eta| < 1.2$

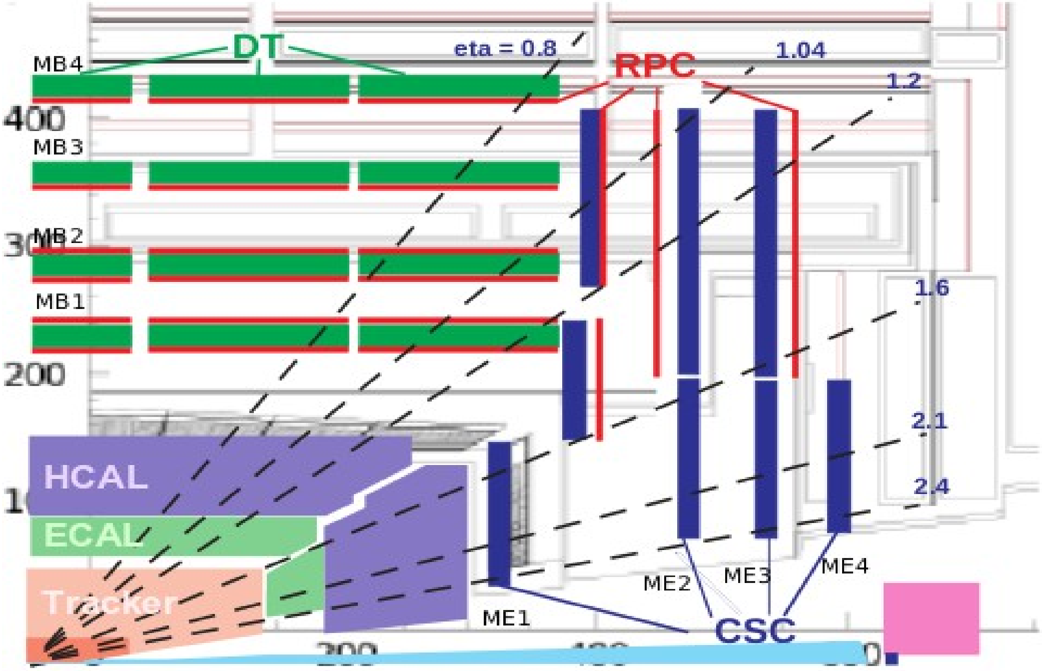
Cathode strip chambers (Ar/CO2/CF4)

$0.9 < |\eta| < 2.4$

Resistive plate chambers ($C_2H_2F_4/C_2H_{10}$)

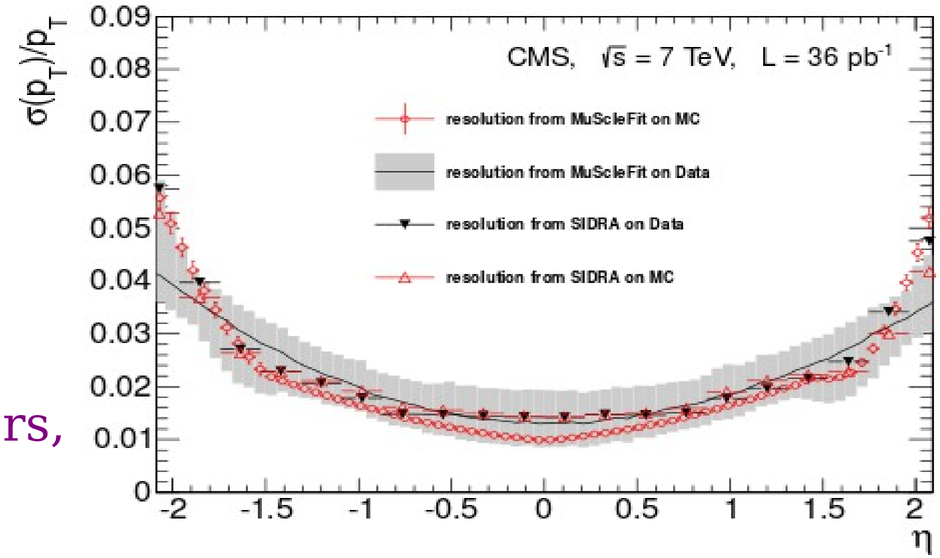
$|\eta| < 1.6$ (also for trigger)

A total of 1400 muon chambers



Expectation:

$$\sigma(p_T)/p_T \approx 1\%(100\ GeV)$$
$$\sigma(p_T)/p_T \approx 10\%(1\ TeV)$$

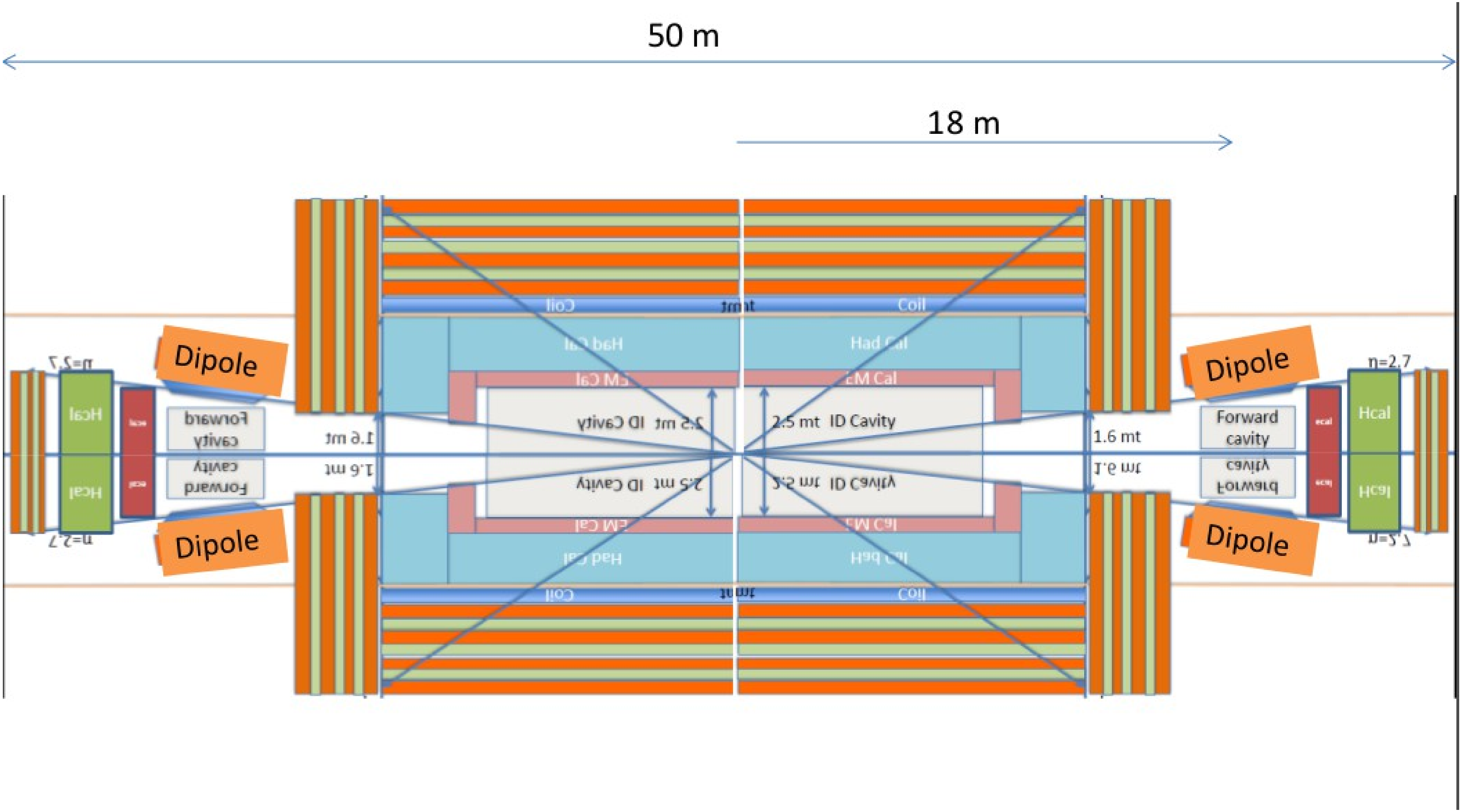


CMS Phase-II extends muon coverage with a Muon station behind the calorimeters, coupled with the pixel extension $|\eta| \sim 4$

We use similar resolution (10%) up to ~10s TeV with $|\eta| < 4$

Approximate detector

CERN FCC Meeting (D.Fournier et. al)



Parametrized detector for 100 TeV proton collider (baseline)

1. Large Solenoid + return yoke: Magnetic Field: 5T, 24m long and 5m radius

2. Central Tracker (including pixel detector)

   - Acceptance within $|\eta| < 4$

   - Momentum resolution $\sigma/p_T \approx 1.5 \times 10^{-4} \oplus 0.005$

   - Efficiencies similar (not same) to CMS Phase-II ECFA studies

3. EM Calorimeter (PbWO4) $\sigma/E = 2.0\%/\sqrt{E} \oplus 0.5\%$

4. Hadronic Calorimeter $\sigma/E = 50\%/\sqrt{E} \oplus 3\%$

5. Forward Calorimeter (needed for VBF and other studies) up to $|\eta| \sim 6$

   $\sigma/E = 100\%/\sqrt{E} \oplus 5\%$

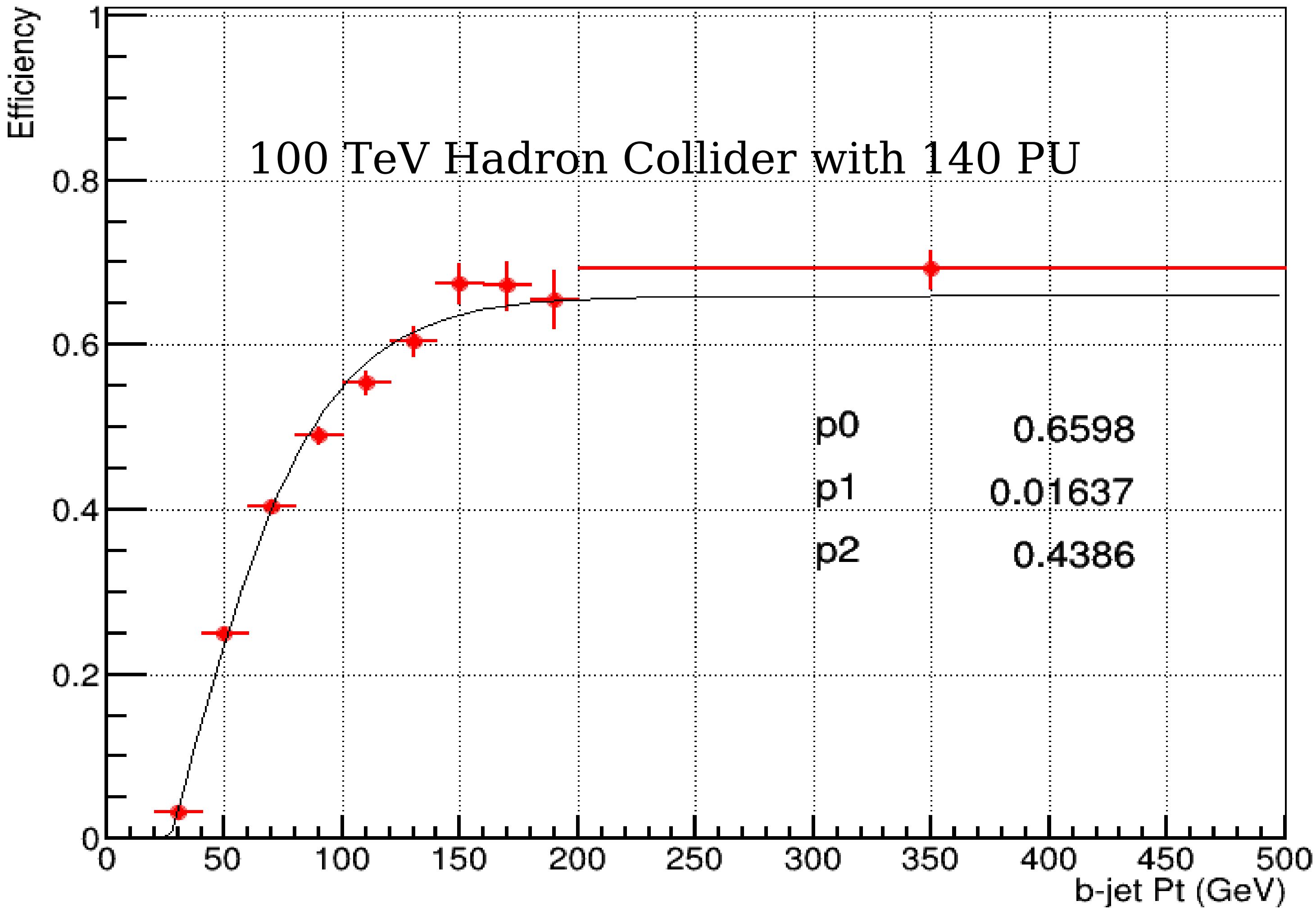
6. Muon detector

   - Acceptance within $|\eta| < 4$

   - Momentum resolution $\sigma/p_T \approx 1\%@100\ GeV - 10\%@10s\ TeV$

   - Efficiencies similar (not same) as CMS Phase-II ECFA studies

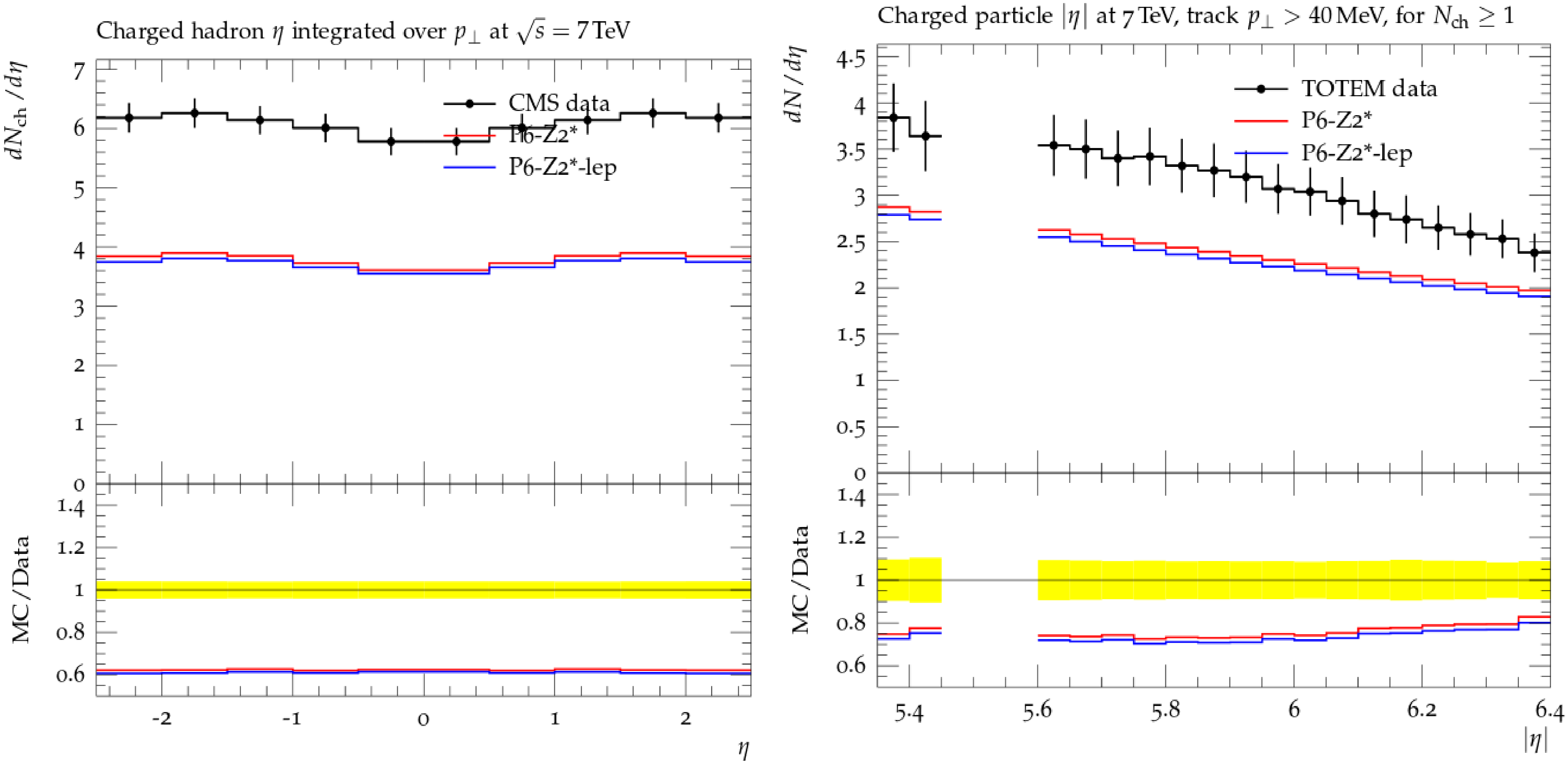
Performance Studies using parameterized detector



Btag Efficiency up to |η| < 4. C-tag rate 18.5%

Also consistent with CMS Phase-II ECFA expectations with similar PU conditions

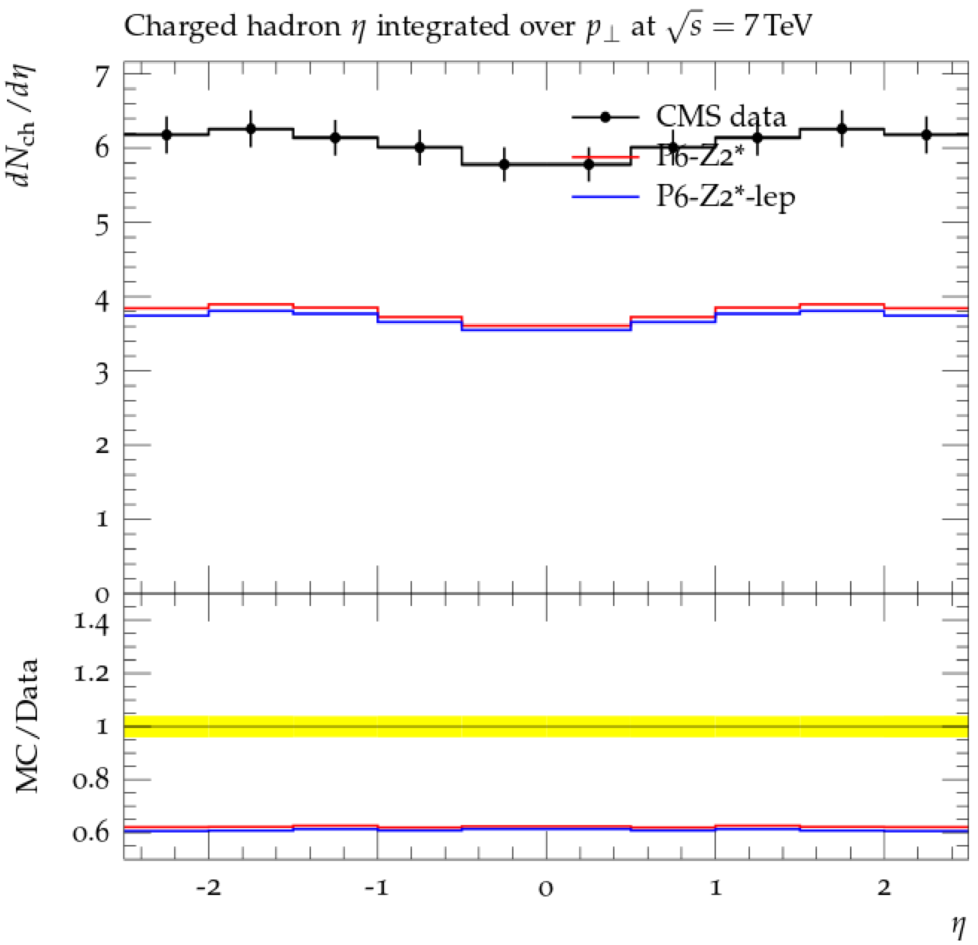
Track Multiplcities

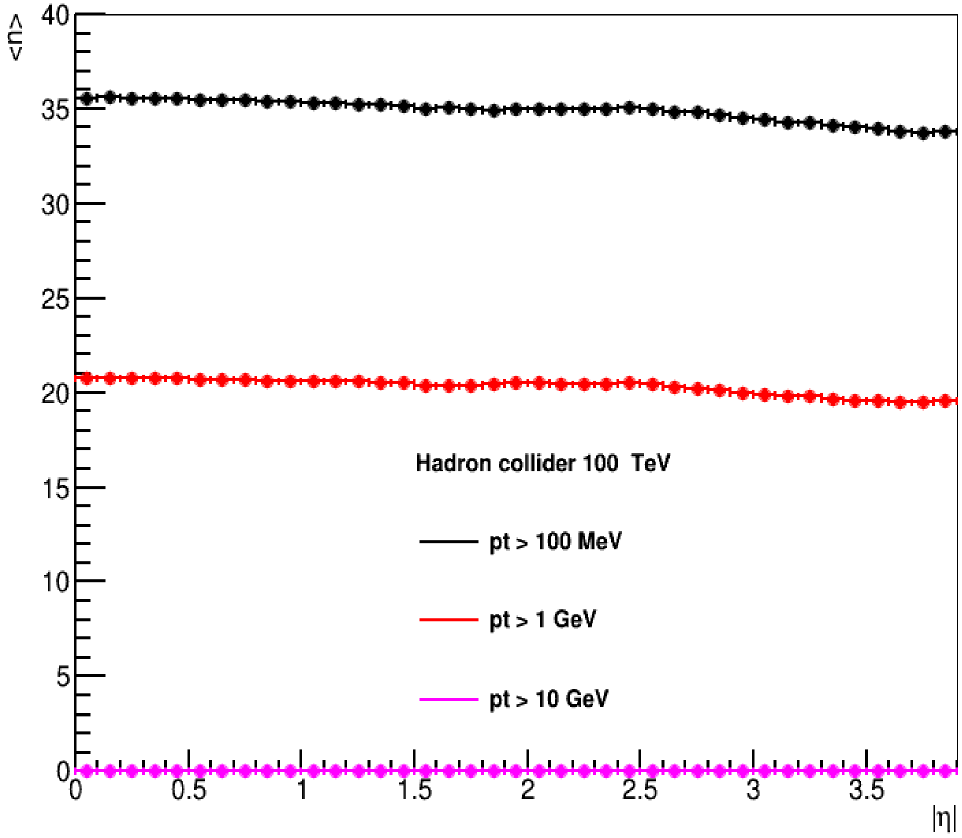


Track multiplicity as measured by CMS with $p_T > 40$ MeV

Mean track multiplicity ~ 6 and drops up to 2 for |η| ~ 6.4

Performance Studies using parameterized detector





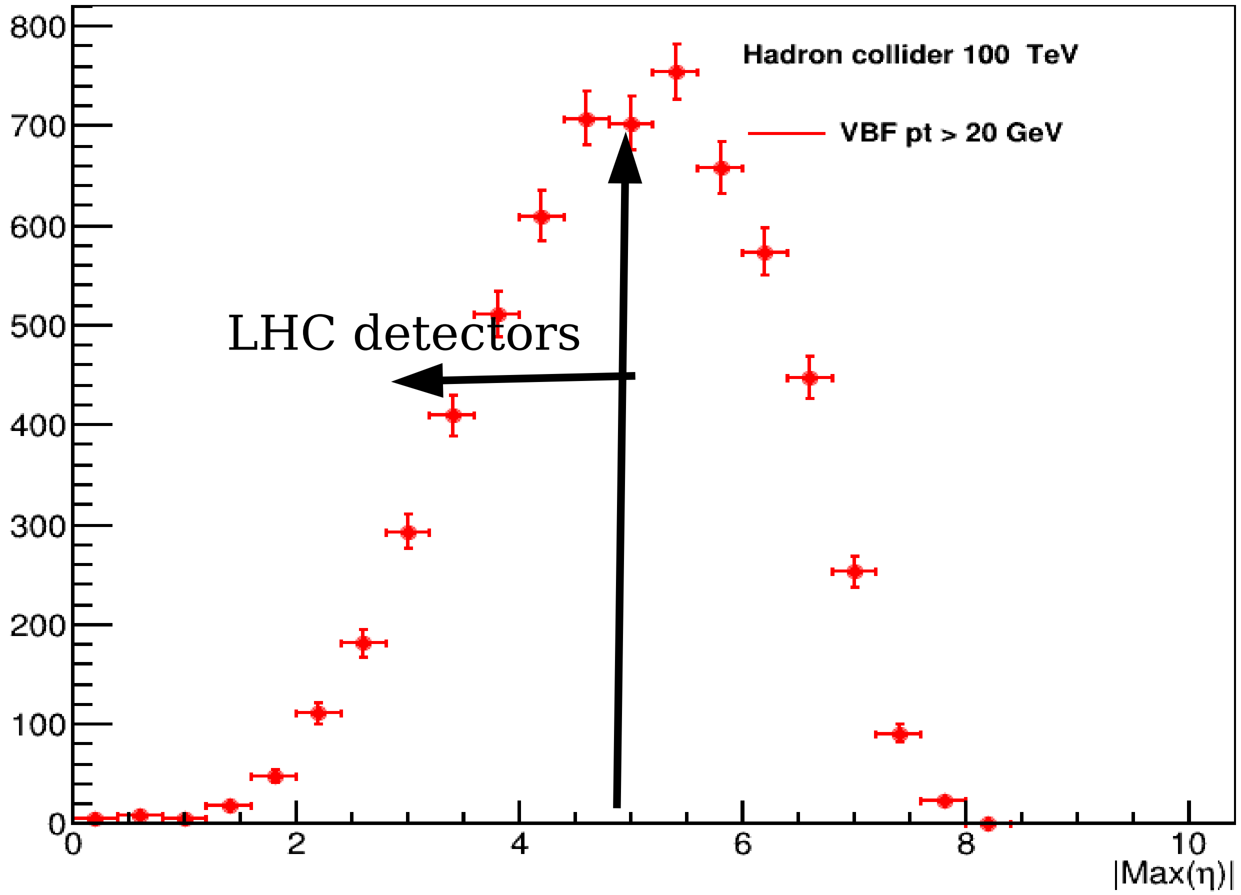
For 100 TeV Collider the mean track multiplicity for p_T > 100 MeV ~ 35

For p_T > 1 GeV, the mean ~ 20 tracks!

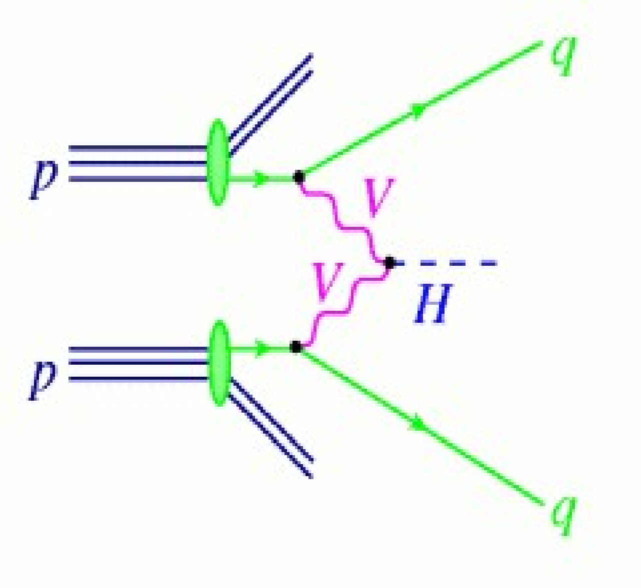
→ Expected pileup cannot be "soft"

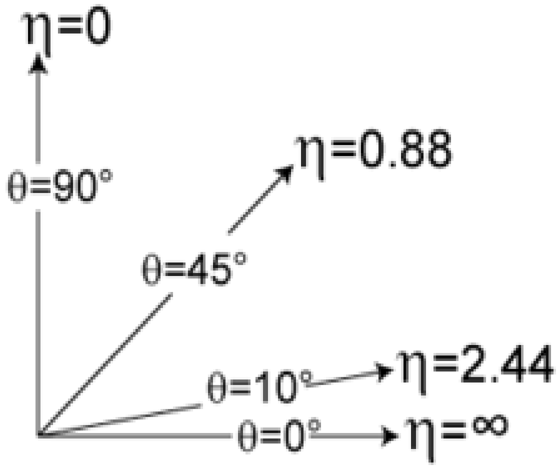
VBF Jets

VBF Jets using 100 TeV LHC



LHC detectors

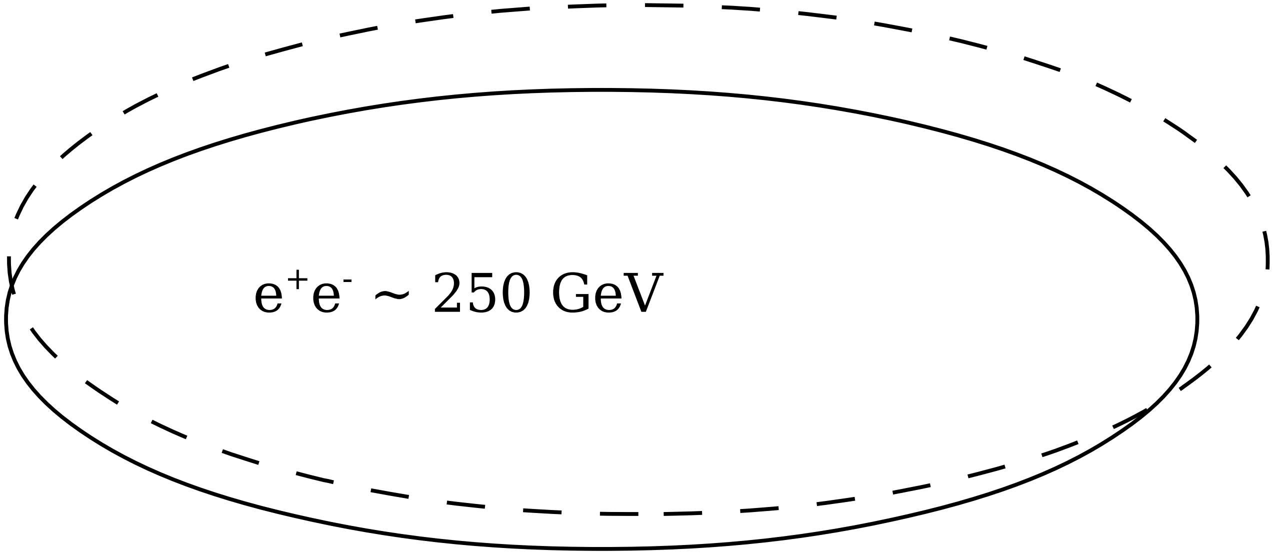




Maximum pseudorapidity for VBF physics

→ Requires large detector acceptance (separate detector like TOTEM?)

Circular $e^+ e^-$ collider - Detectors



Physics goals for e$^+$e$^-$ collider

Benchmarks for ~250 GeV Collider

1. Precise measurement of Higgs mass and the cross section

$$e^+e^- \rightarrow Zh, Z \rightarrow e^+e^-, \mu^+\mu^-, h \rightarrow X$$

   - Lepton and Photon ID
   - Momentum resolution in the tracker

2. Measurement of higgs branching fractions

$$e^+e^- \rightarrow Zh, Z \rightarrow \nu\nu, h \rightarrow c\bar{c}, \mu^+\mu^-$$

   - Heavy flavor tagging performance
   - Secondary vertex reconstruction
   - c-tagging

3. Measurement of BR for higgs decaying to charm

$$e^+e^- \rightarrow Zh, Z \rightarrow q\bar{q}, h \rightarrow c\bar{c}$$

   - Charm tagging
   - Able to separate charm from the light jets (mistag)

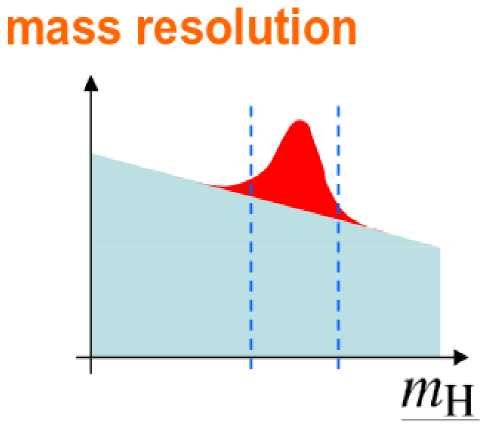
Representative tests of detector capabilities.

- Vertex detection, tracking and Calorimetry (Particle flow) are important

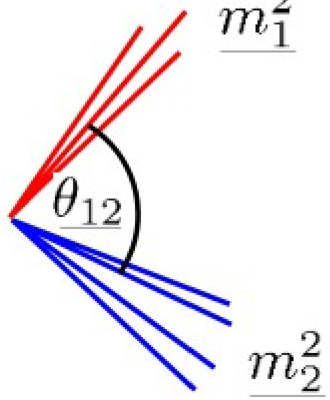
Jet Energy requirements

Narrow resonances (di-jet mass resolution)

- Need best possible di-jet mass resolution

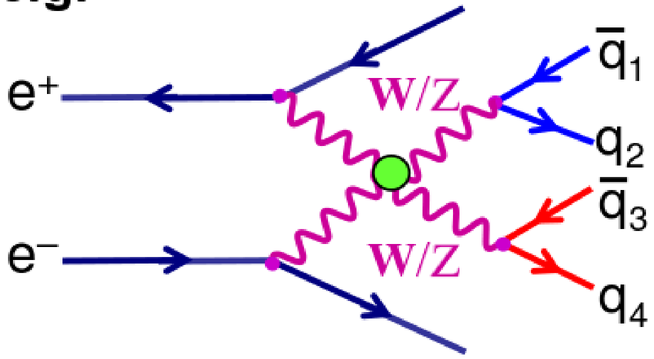


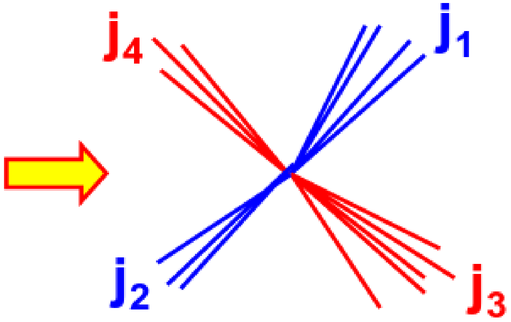
$$\text{signif.} \propto \frac{S}{\sqrt{B}} \propto (\text{resolution})^{-\frac{1}{2}}$$

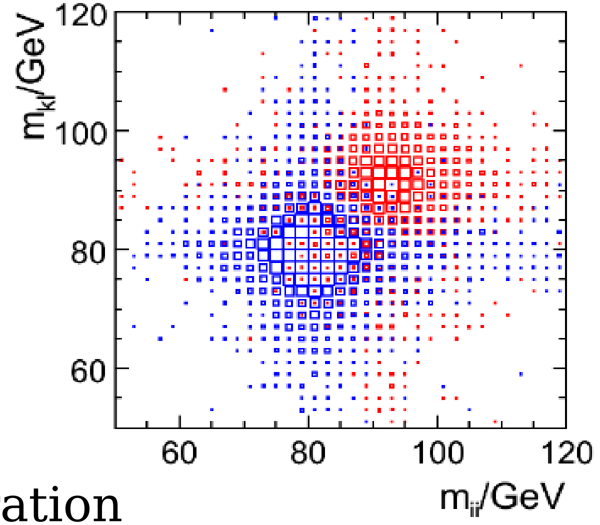


Need to separate W/Z hadronic decays

e.g.







3-4% jet energy resolution can give decent W/Z separation

Detector Choices – Lessons from ILC

Magnetic Field: 5 Tesla field within a lateral distance of 15m

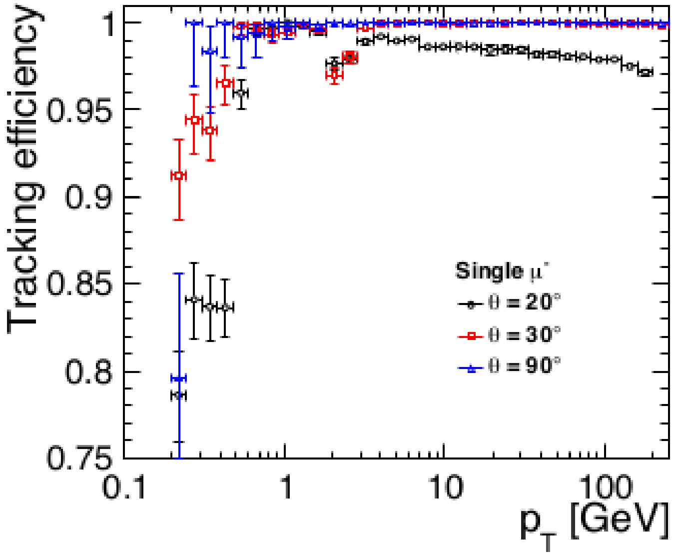
Particle Flow Detector

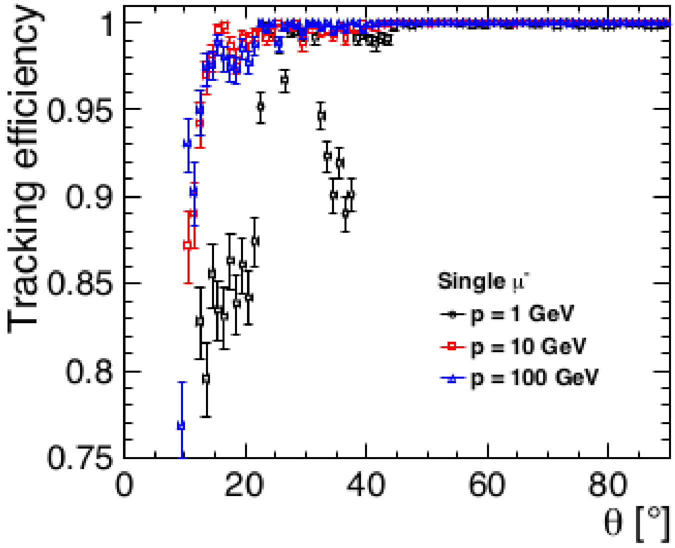
Vertex Detector: Combination of MAPS, SOI, 3D technologies are being evaluated

Tracker :

ILD: hybrid tracking system consisting of a large-volume gaseous TPC tracking detector surrounded by silicon tracking layers

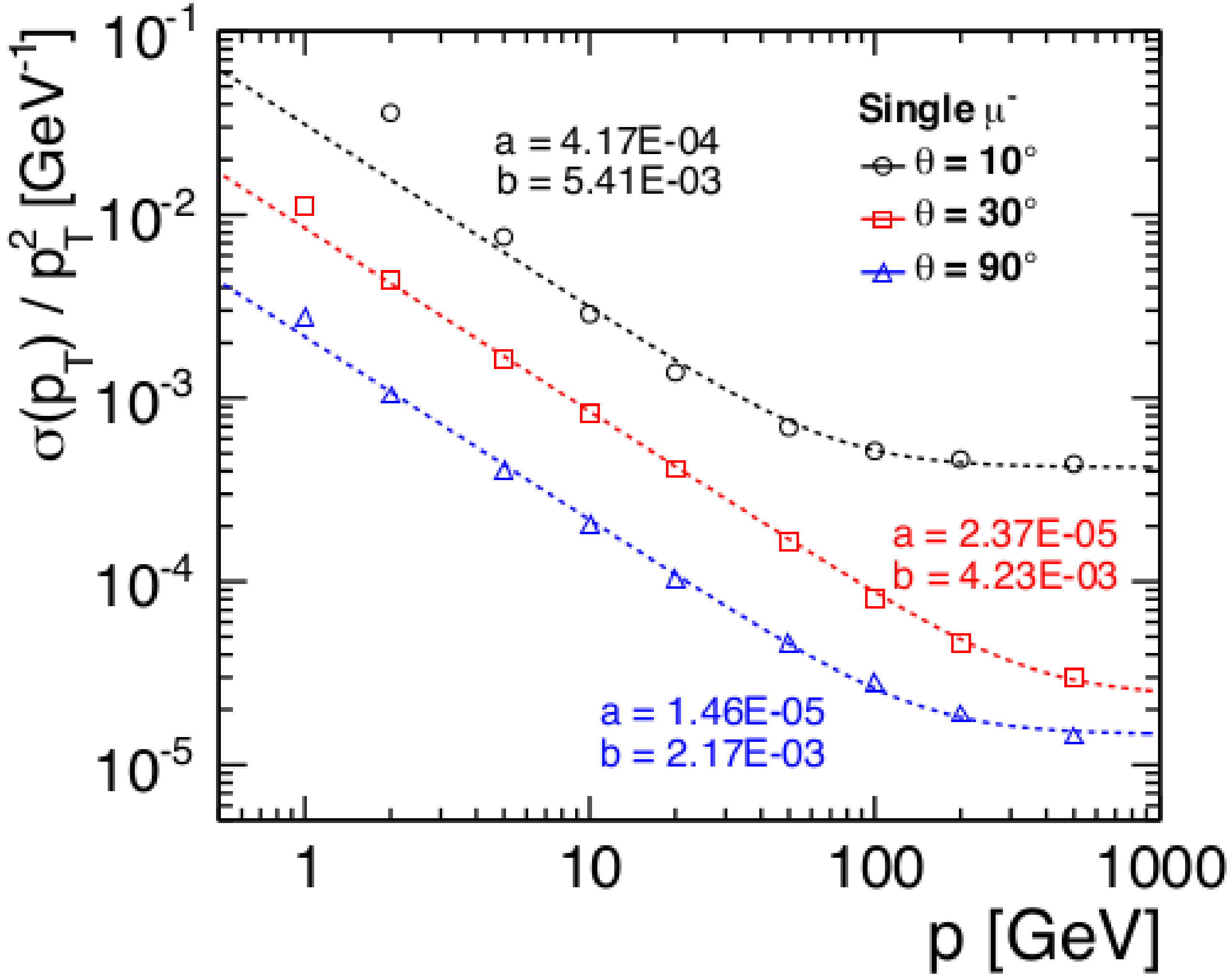
SiD: detector is based on silicon technology only





Detector Choices – Lessons from ILC

The track momentum resolution can be obtained using:



$$\sigma(p_{\mathrm{T}})/p_{\mathrm{T}}^2 = a \oplus \frac{b}{p \sin\theta}.$$

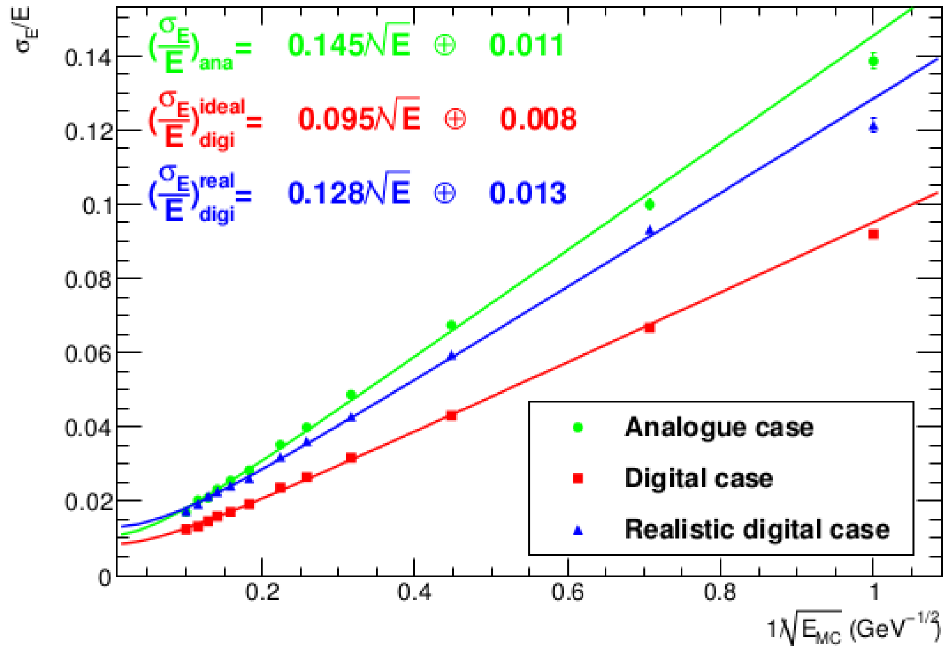
Detector Choices

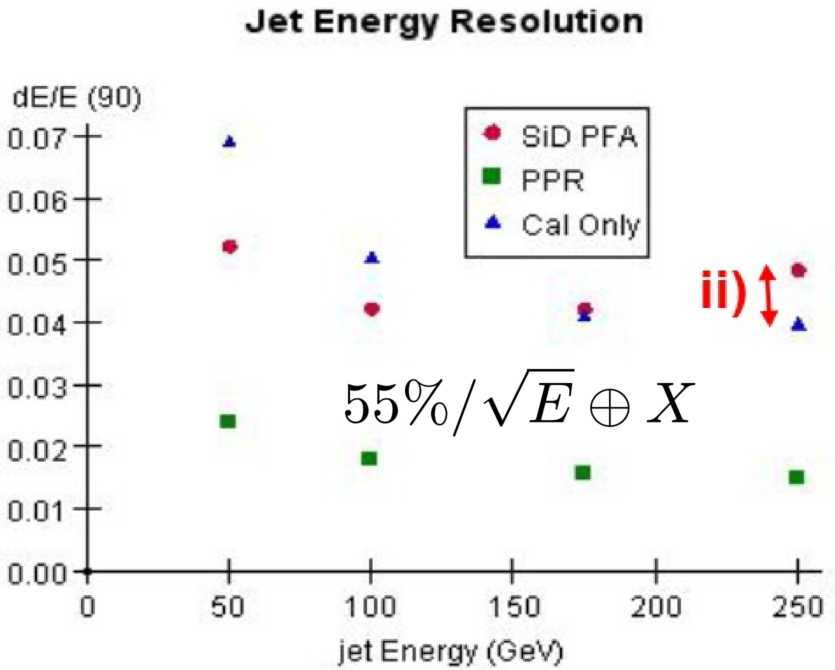
Highly compact silicon tungsten ECAL by the SiD collaboration

EM energy resolution $\sigma/E = 0.17/\sqrt{E} \oplus 1\%$

Digital HCAL:

- glass RPCs which has the front-end electronics embedded in the active layers
- in-depth exploration of the digital approach to hadron calorimetry





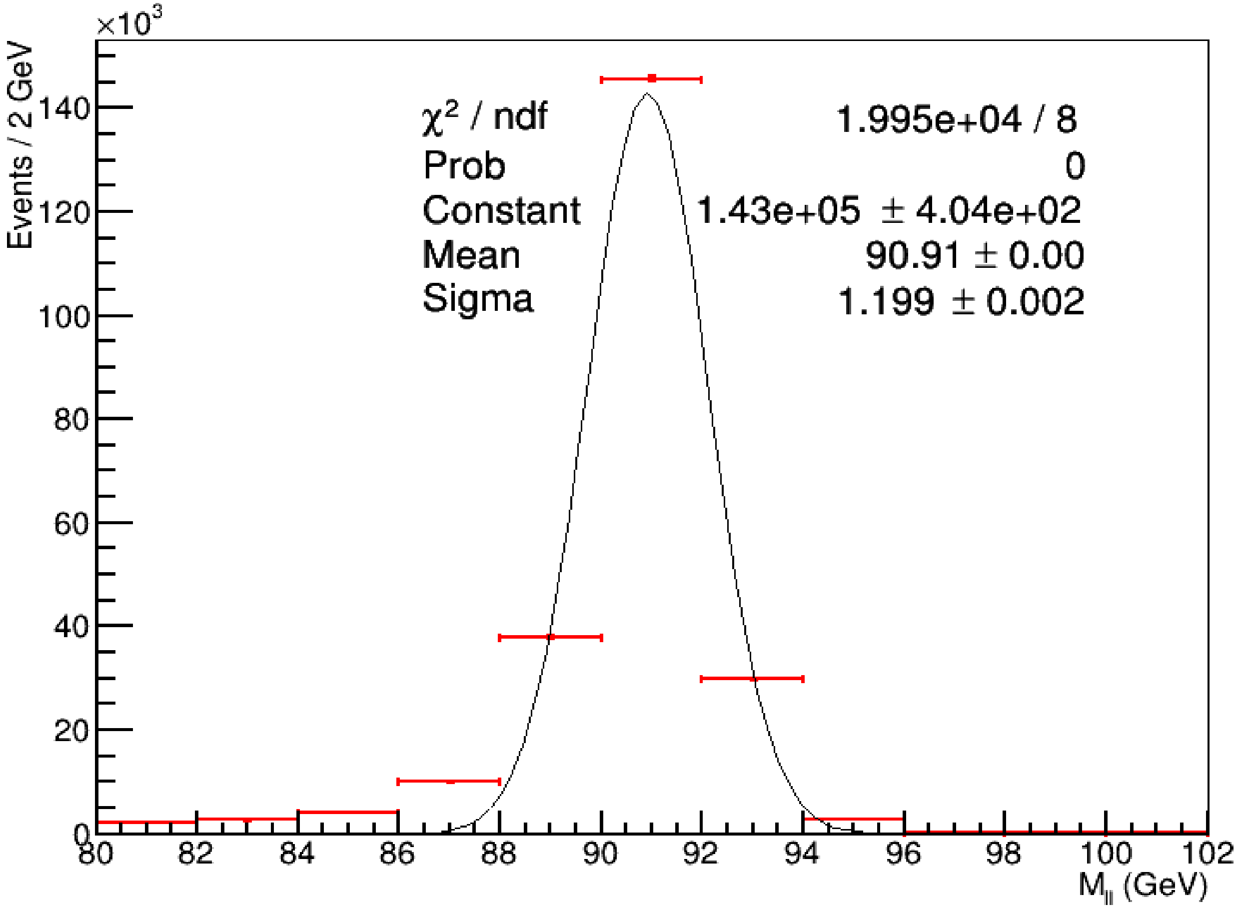
$$55\%/\sqrt{E} \oplus X$$

The muon system is expected to be in seven layers of 18 cm steel and three layers of 36 cm steel in an octagonal barrel geometry with either Scintillating strips or RPCs

Parameterized detector for e^+e^- ~ 250 GeV

Putting all of these together, we can have a parameterized detector

The invariant mass of the dileptons (e^+e^-, $\mu^+\mu^-$) in ZH events



Very comparable to the CMS based TLEP simulation with Z boson mass resolution

$Z(e^+e^-)$ = 1.5 GeV, $Z(\mu^+\mu^-)$ = 1.2 GeV. (arXiv:1208.1662)

Detailed physics studies using this can start now

Summary and Conclusion

Detectors for future cicular collider will have numerous challenges

→ Opportunities to develop novel technologies

As was done in the case of Snowmass (as well as Phase-II CMS ECFA)

parametrized detector studies with reasonable assumptions can be vital

→ It can help us with the needed Physics benchmarks for the collider

→ Identify key areas where more R&D might be needed

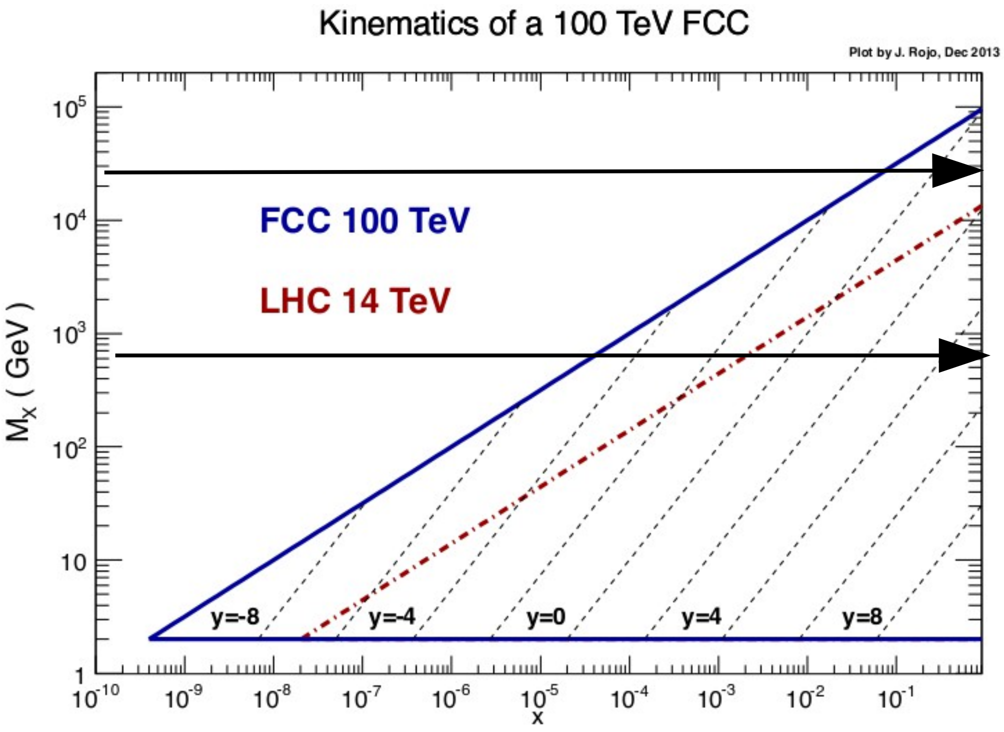
For this meeting:

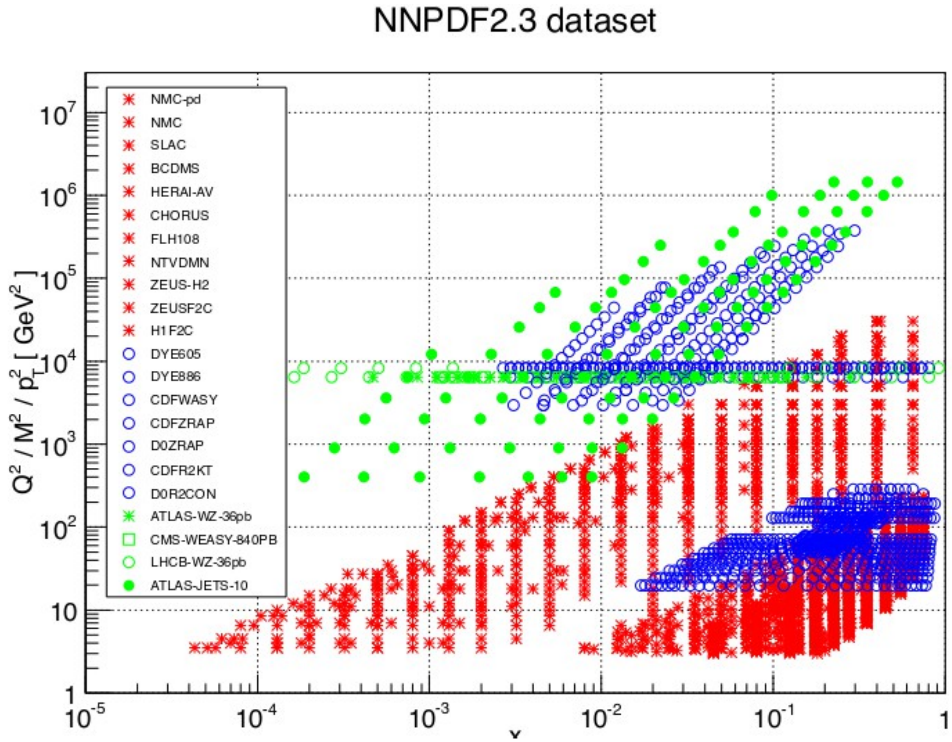
We can start the Physics and object performance activities now!

Backup slides

Kinematical Coverage of 100 TeV FCC

J. Rojo (CERN)





Large region of coverage as a function of M_x between 14 and 100 TeV FCC

Essentially no constraint for $x < 10^{-4}$

Poor constraint for high x

PDF fits rely on QCD evolutions → EW effects will be needed for multi-TeV regions

→ Very important for electroweak (SUSY) production

P. Meade et. al started looking into this (opportunity for collaboration)