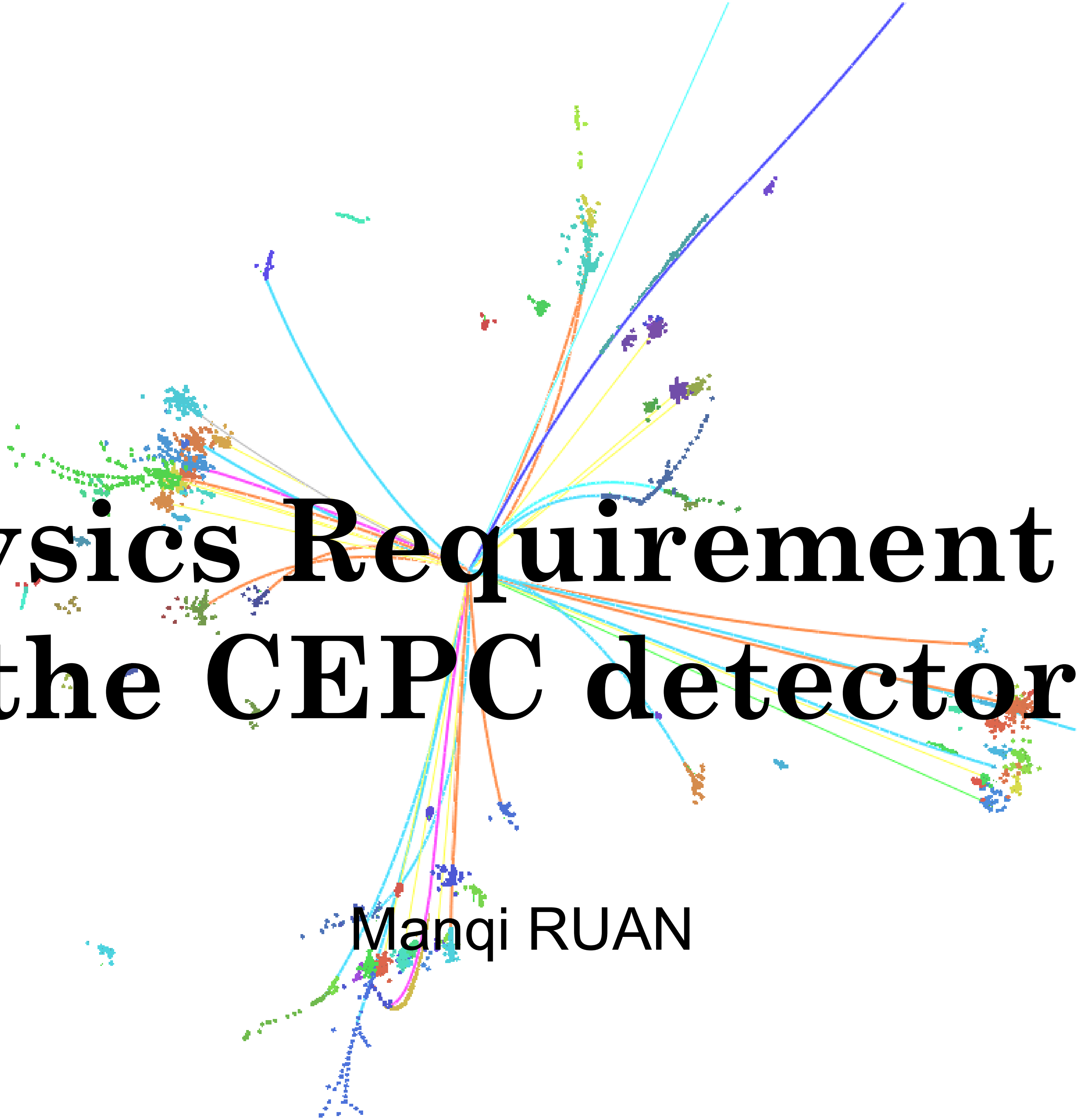
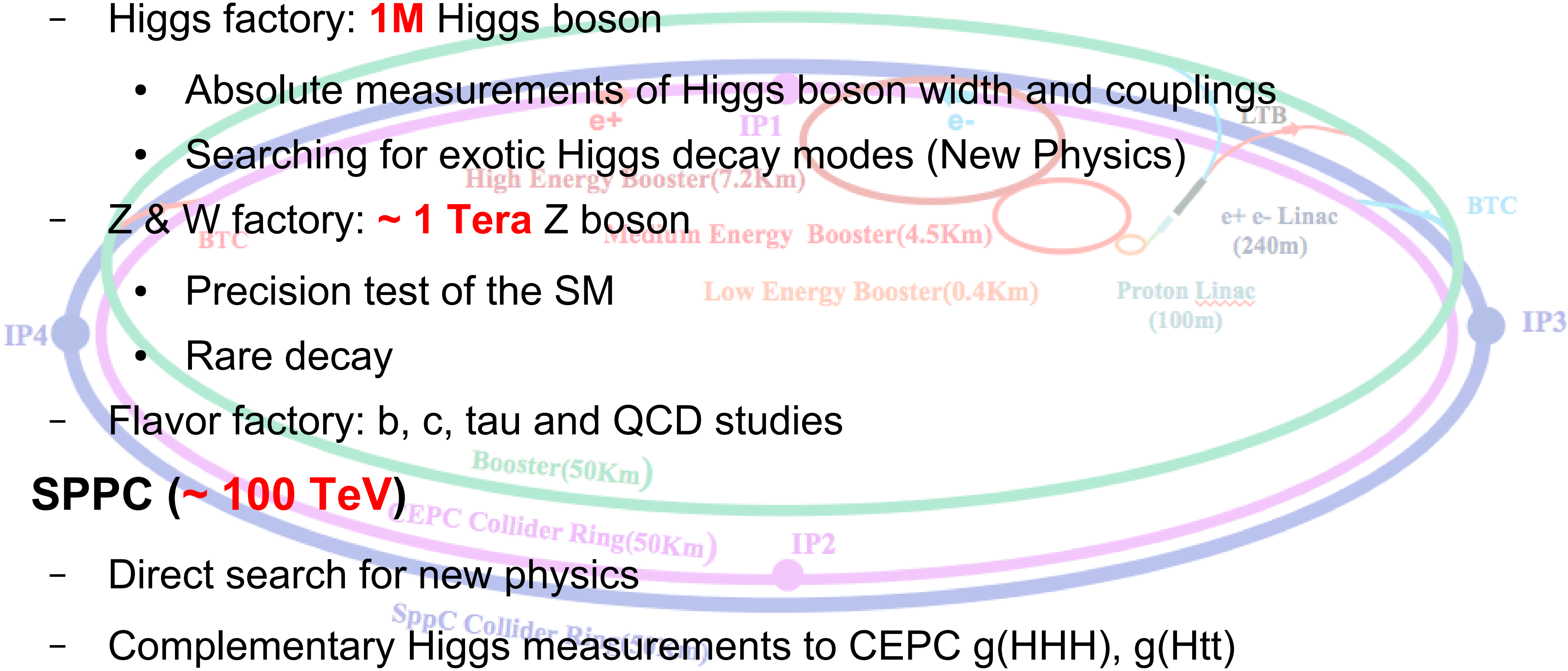


Physics Requirement for the CEPC detector

Manqi RUAN

Science at CEPC-SPPC

- **Tunnel ~ 100 km**
- **CEPC (90 – 250 GeV)**
  - Higgs factory: **1M** Higgs boson
    - Absolute measurements of Higgs boson width and couplings
    - Searching for exotic Higgs decay modes (New Physics)
  - Z & W factory: **~ 1 Tera** Z boson
    - Precision test of the SM
    - Rare decay
  - Flavor factory: b, c, tau and QCD studies
- **SPPC (~ 100 TeV)**
  - Direct search for new physics
  - Complementary Higgs measurements to CEPC g(HHH), g(Htt)
  - ...
- **Heavy ion, e-p collision...**



Complementary

Detector & performance

- Performance: Identify & Measure Key Physics objects
  - Identification: to suppress the contamination from the reducible background
    - i.e., identification of isolated lepton is critical to reject the WW→lνqq background from the llH Signal
  - Accurately measure their Position/Momentum: to reject the irreducible background & measure the differential Xsec
    - i.e., distinguish the ZZ background from ZH, with same final states of llqq.

- Objectives (Ideal):
  - Saturation the performance: further improvement on detector performance won't significant improvement in the physics result
  - Reconstruct all the final state particle, and their generation/decay information, especially for particles inside the jet (essential for flavor physics, i.e., b→B*→B→D*→D→...)

Requirements at the CDR

Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) =$ $2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} =$ $5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E =$ $3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E =$ $\frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

Table 3.3: Physics processes and key observables used as benchmarks for setting the requirements and the optimization of the CEPC detector.

Key Physics Objects

Tracks
Photon and pi-0

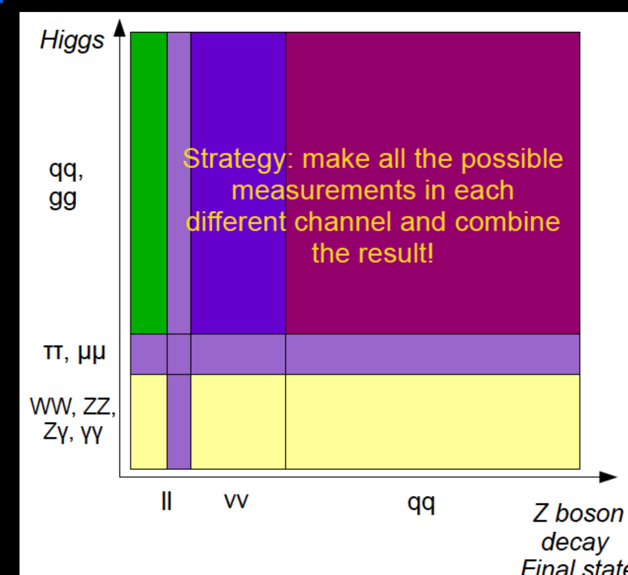
Leptons:
- Isolated,
- Inside jets

Pid: Charged Kaon, Proton

Hadronic System:
- BMR
- Jets: Energy, Charge & Flavor

VTX
Exotic Objects: Long Lived Particles, et. al

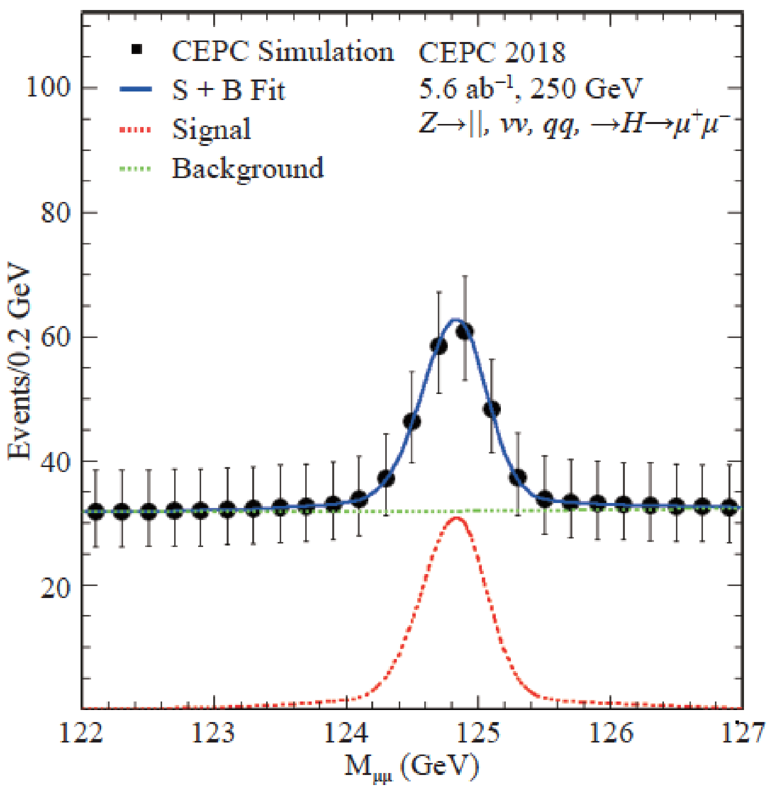
DRUID, RunNum = 0, EventNum = 23

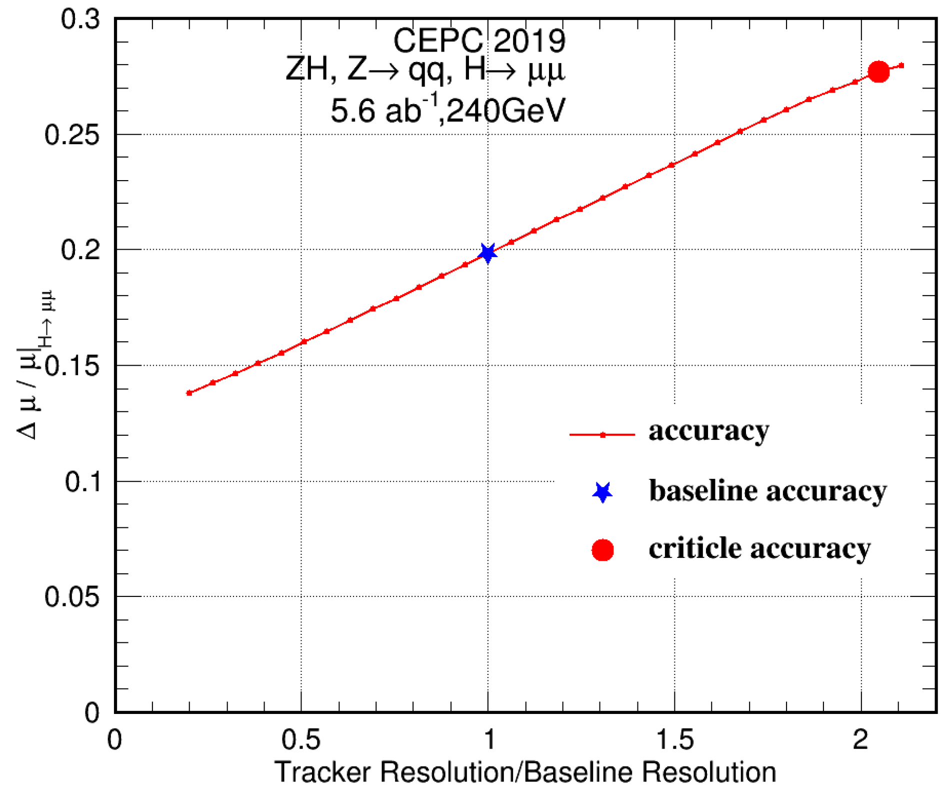


Tracks

- Acceptance |cos(theta)| < 0.99 – 0.995...
- Momentum threshold
  - ~o(0.1 GeV) for Flavor Program ($D^* \rightarrow D + \pi$)
- Efficiency: should ~ 100% within the energy & solid angle acceptance
- Momentum resolution:
  - $\delta(m)/m \sim 0.1\%$ for Higgs with di-muon final state
  - $\delta(m)/m < 0.1\%$ (?) for narrow hadrons in the flavor program
    - Heavy flavor Hadron: D, B, ...
    - Lambda, Ks, Phi...
    - J/psi, Upsilon, ...
- *Balance the Material budget (multiple scattering: accuracy & efficiency lose) and accuracy/rate acceptance...*

H→μμ at CEPC Baseline



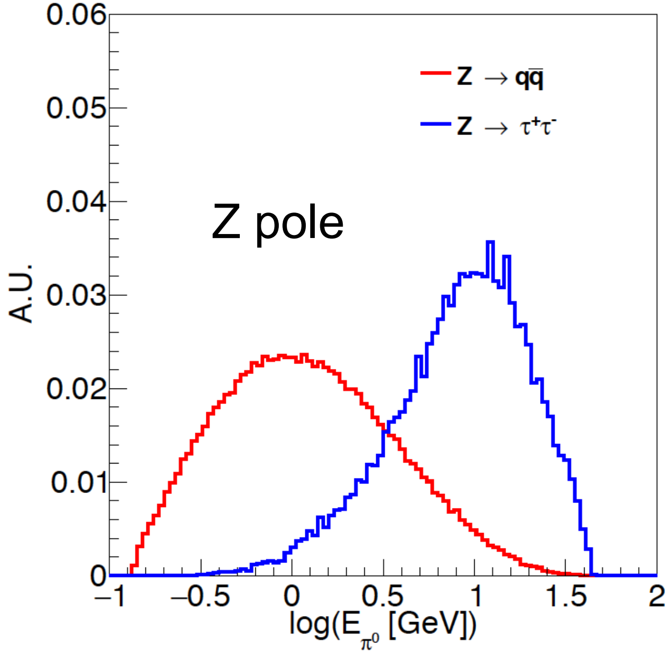


- δ(m)/m ~ 0.2%

Photon & π^0

- Larger acceptance: for ISR photon tagging (Need further quantification) as well as luminosity measurement
- Threshold: ~o(100) MeV;
- Low energy photons < 20 GeV, mostly from π^0 decay
  - Flavor physics: narrow resonances
  - Exotic
- High energy photons: 20 – 100 GeV
  - $H \to \gamma\gamma$
  - Measurements with $Z\gamma$ events (ISR),
    - Neutrino generation measurements
    - Jet calibration, etc
- Good linearity for 3 orders of magnitude (100 MeV – 100 GeV)

π^0: energy range



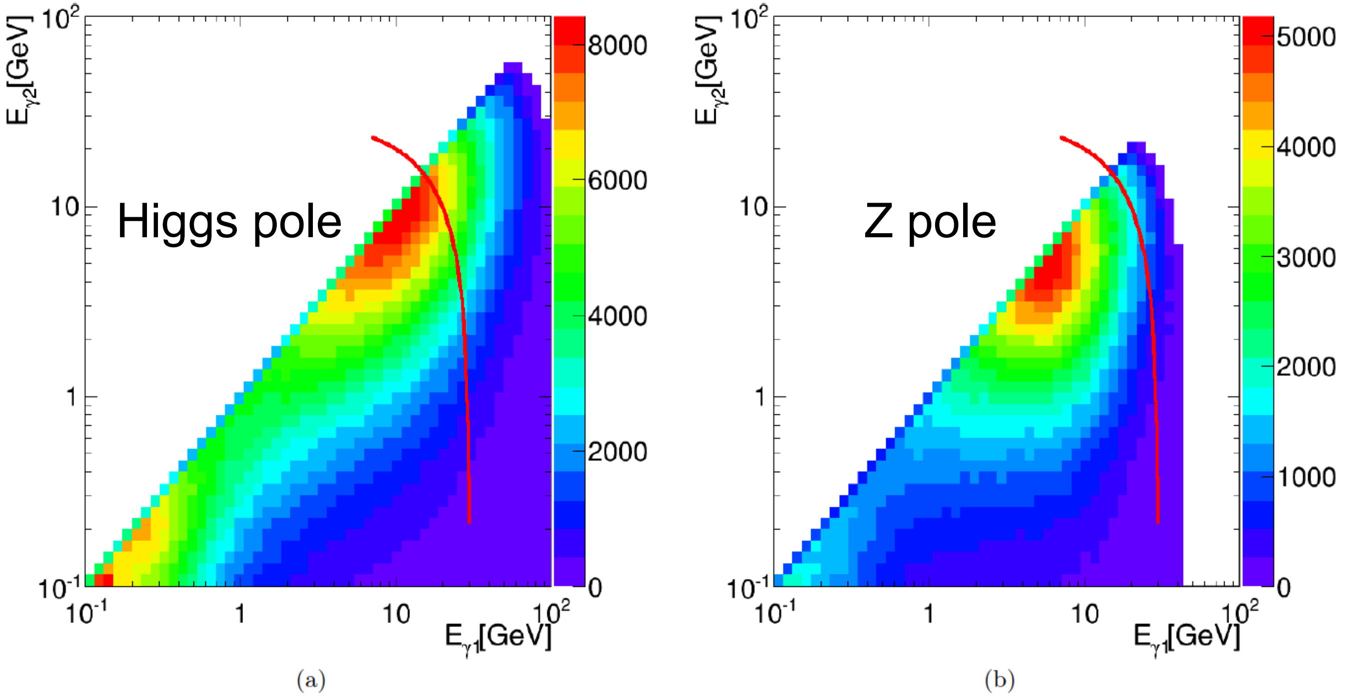
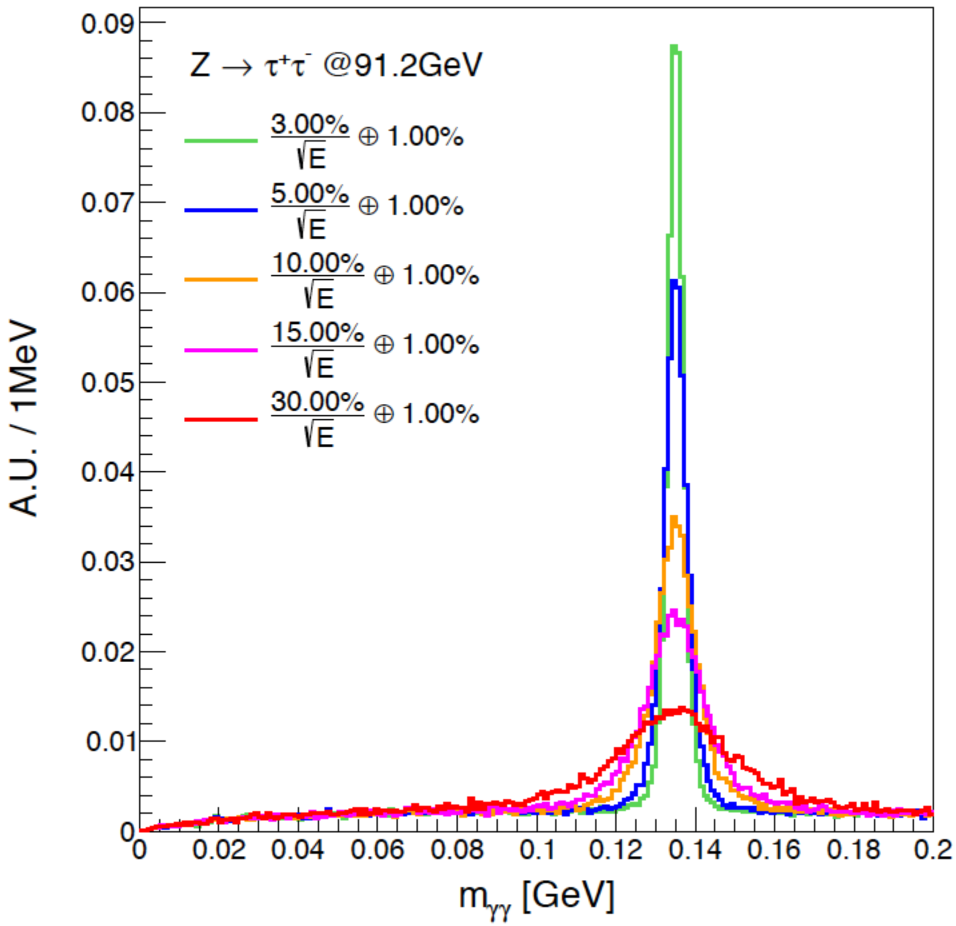


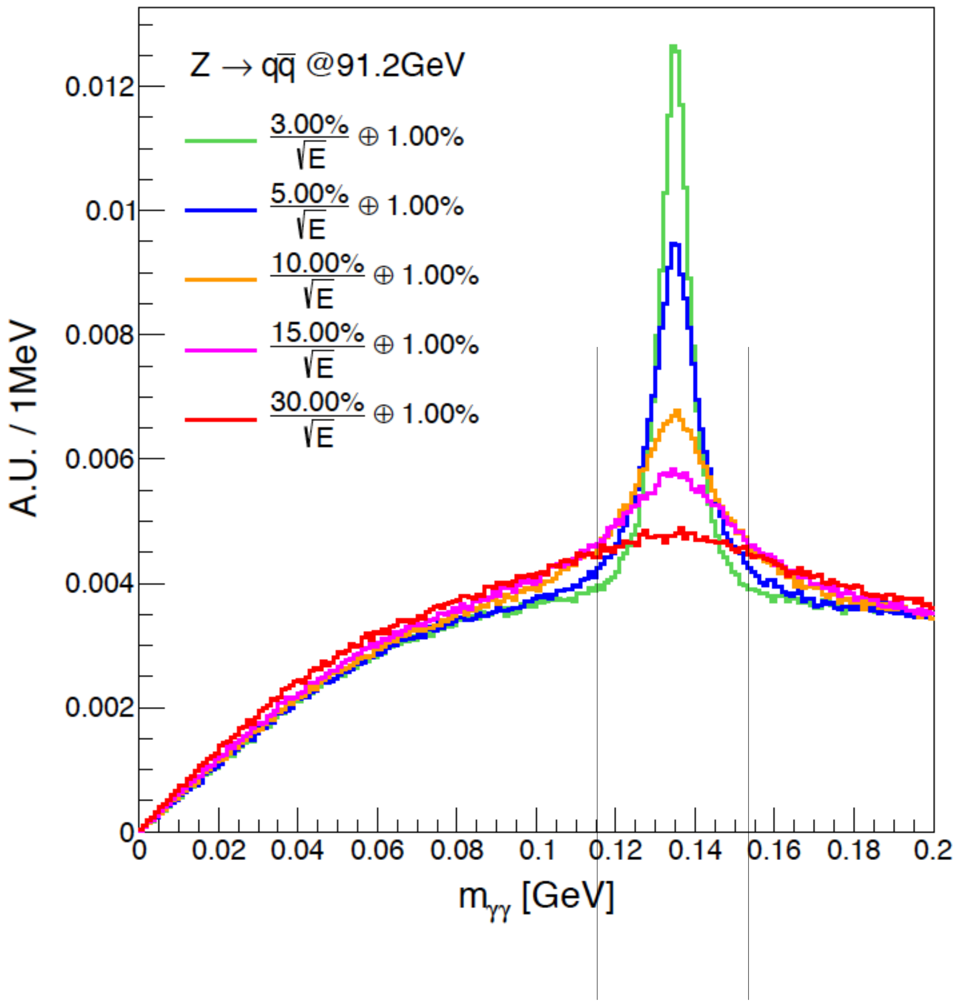
Fig. 14: The generated π^0 distribution as a function of the energies of di-photons from $\pi^0 \to \gamma\gamma$ in inclusive Higgs (a) and $Z \to \tau\tau$ samples (b). $E_{\gamma 1}$ is the energy of the leading photon. $E_{\gamma 2}$ is the energy of the sub-leading photon. The red line is the function of $E_{\gamma 1} + E_{\gamma 2} = 30$ GeV.

- π^0 energy (rest-mass, 30 GeV – 60 GeV): photon threshold ~ o(100) MeV
- At Z pole: be able to separate photons from Pi-0 decay, up to 30 GeV

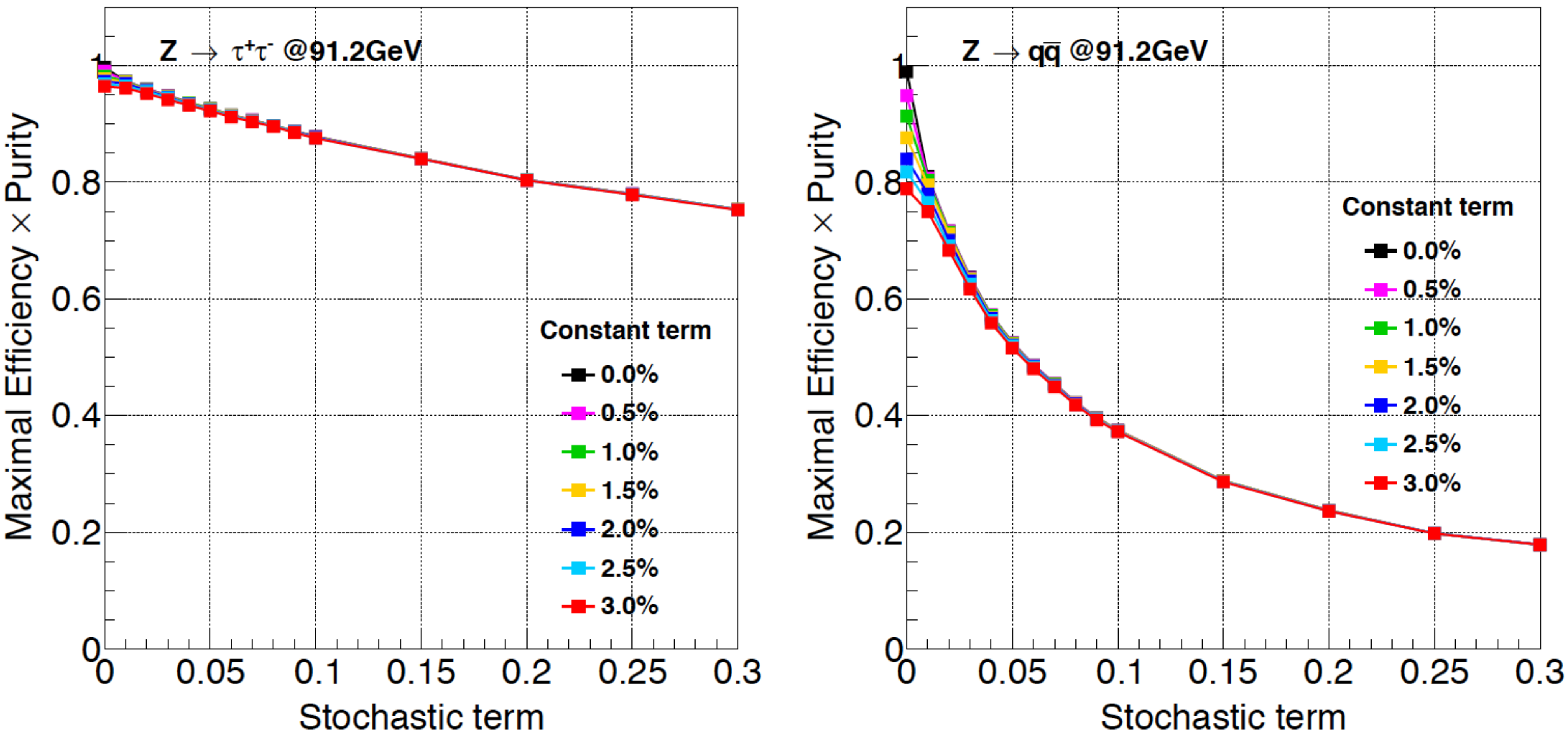
π^0: truth level analysis

Yuexin





Impact of EM resolution on π^0 finding



Dependency on π^0 energy

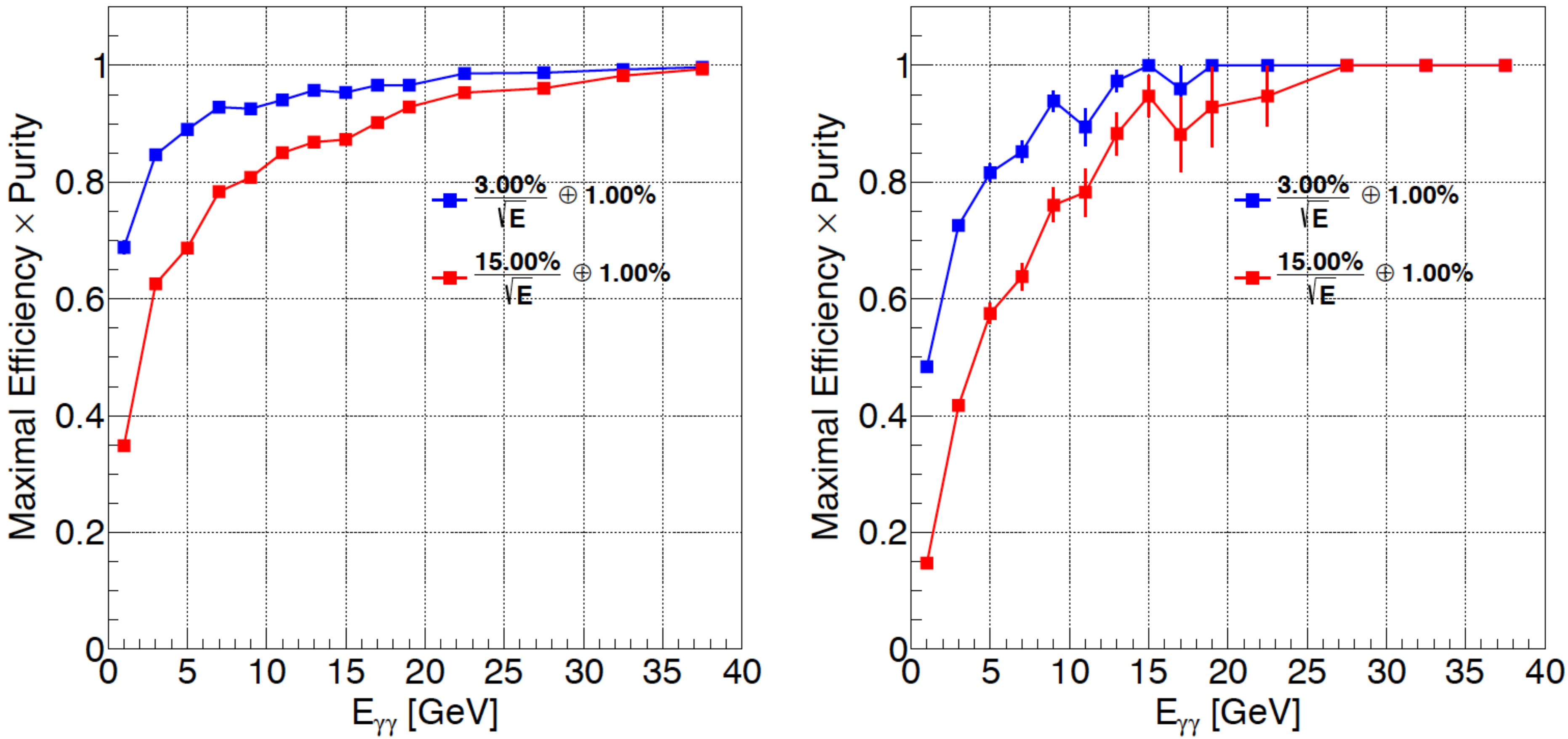


Figure 13: Energy differential maximal $\epsilon \times p$ for $Z \to \tau^+\tau^-$ (left) and $Z \to q\bar{q}$ (right).

...Surely the low energy pi-0 reconstruction benefit more from a better EM resolution...

π^0: energy spectrum decomposition

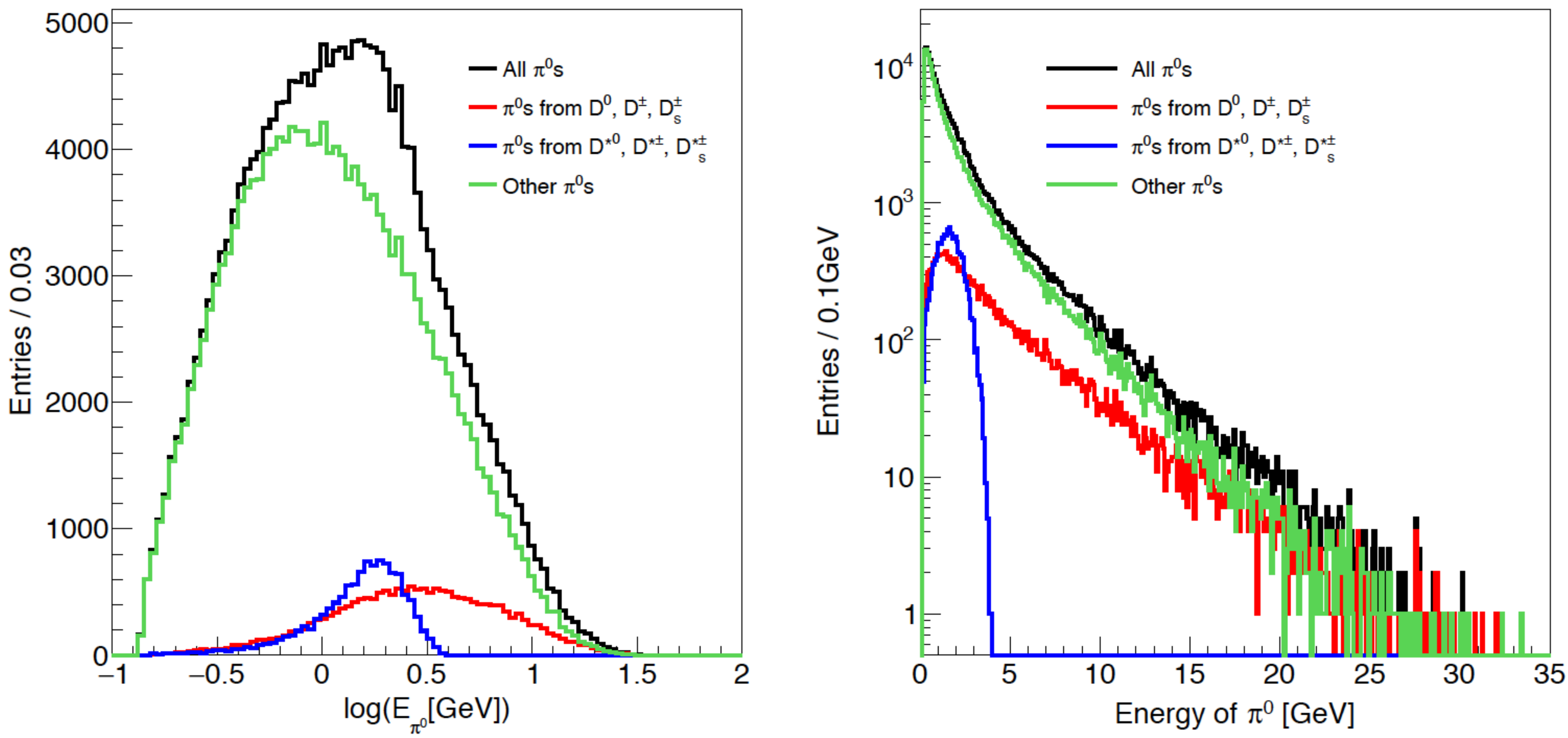


Figure 13: Energy spectrum of π^0 from different origins in $Z \to c\bar{c}$.

π^0 reco

- ECAL resolution is critical: improving the ECAL resolution from 15%/sqrt(E) to 5%/sqrt(E) (with 1% constant term) significantly improve the inclusive π^0 reconstruction efficiency
  - From 85% to 92% at Z→tautau
  - From 30% to 50% at Z→qq

- Low energy π^0 is more sensitive to ECAL energy resolution.

- Further quantification needs physics benchmarks
  - Narrow States → $n*\pi^0$ + X, X are a set of charged Particle. For example Bs → $2\pi^0$

Pid: Identify charged hadrons with energy up to 20 GeV...

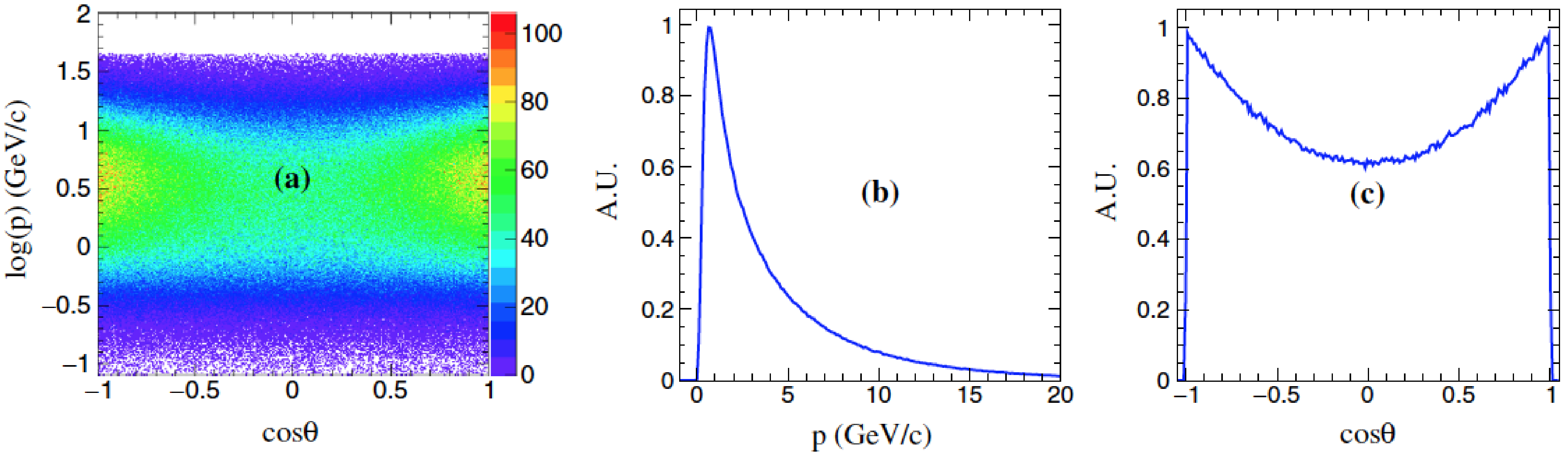
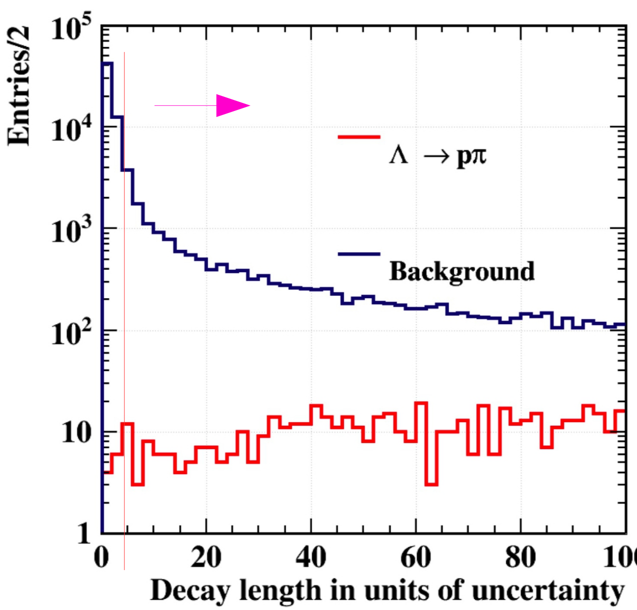
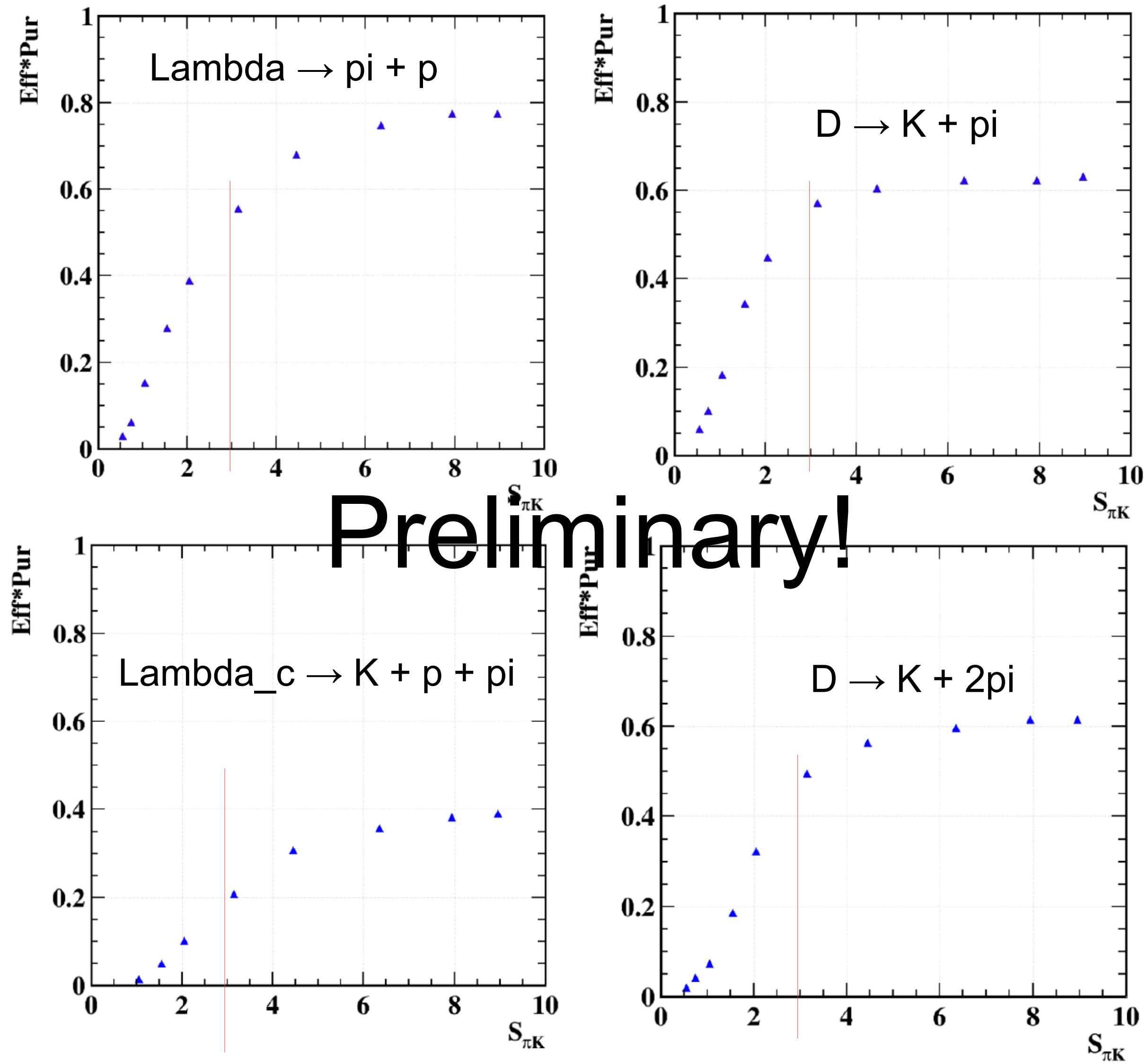


Fig. 3 Kinematic distribution of kaons in $e^+e^- \to Z \to q\bar{q}$ MC events as a function of $\log(p)$ and $\cos\theta$ (**a**), p (**b**), and $\cos\theta$ (**c**)

Pid & Objective Hadron finding

$$S_{AB} = \frac{|I_A - I_B|}{\sqrt{\sigma_{I_A}^2 + \sigma_{I_B}^2}},$$

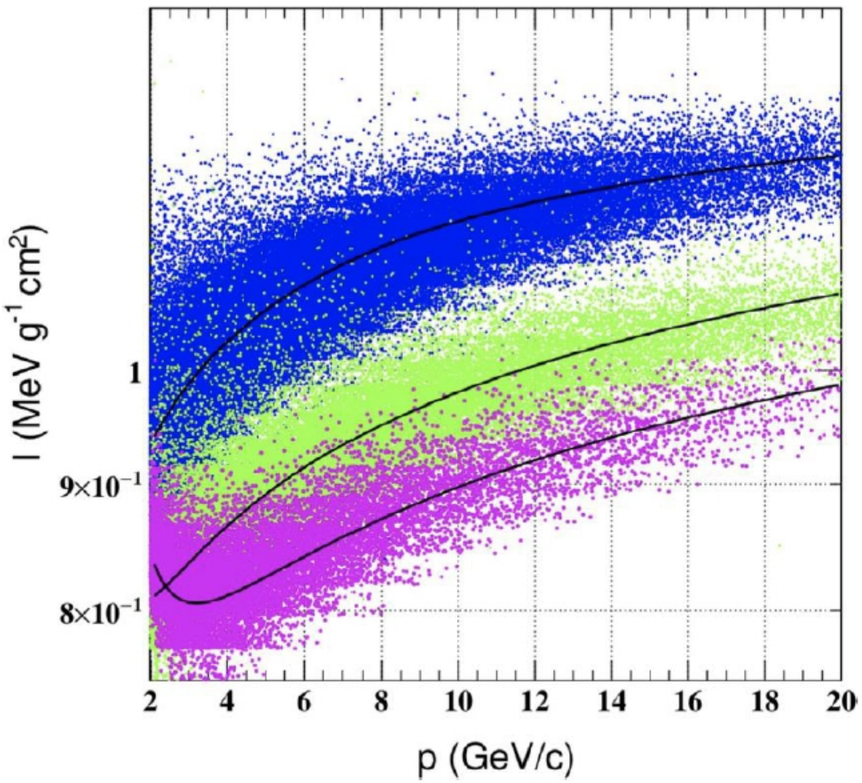




Preliminary!

Pid & dEdx

Fenfen, Taifan, Zhiyang, etc



MC result of single-particle events with the theoretical prediction by the Bethe equation [16] overlaid. In the right plot the dots are from simulation of $e^+e^- \to Z \to q\bar{q}$ events

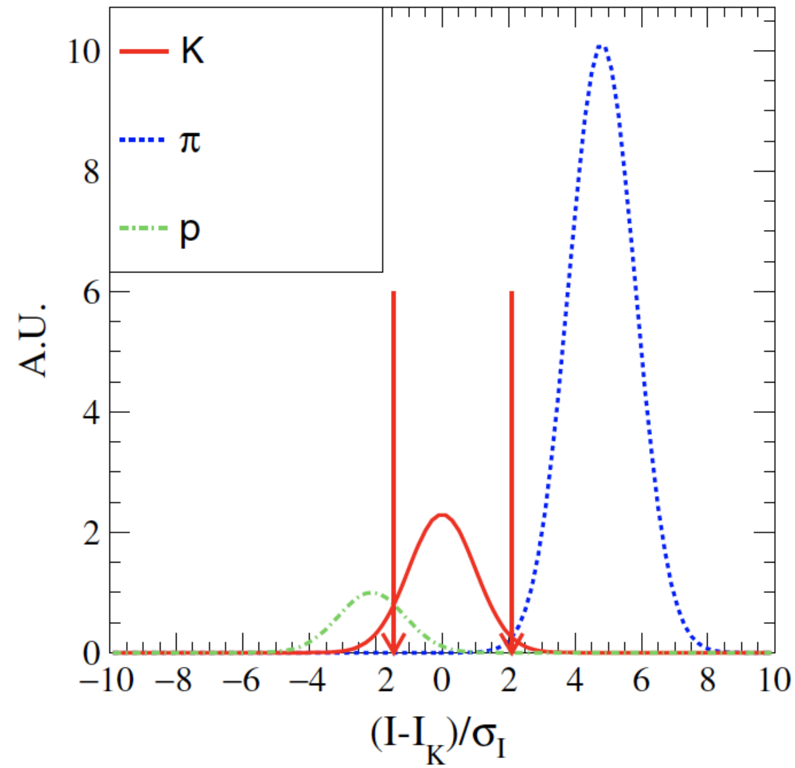


Fig. 6 The scaled spectra of $(I - I_K)/\sigma_I$ using dE/dx measurements alone for particles with a momentum of 5 GeV/c, assuming a 20% degradation. The relative populations are $N_\pi = 4.4N_K$ and $N_K = 2.3N_p$ according to MC simulation. The intersections marked by the arrows are chosen as the cut points

Pid & dEdx

- Preliminary:
  - Energy Spectrum: identify charged hadrons up to 20 GeV...
  - 3σ separation of pi-Kaon, corresponding to 2% of dEdx resolution, is appreciated for the mass hadron reconstruction with kaon/proton in its decay final state
  - Need to have further physics benchmark analysis.

- For objects with kaon and/or proton in its decay product: performance depends on
  - Momentum (fully charged final state)
  - Hadron separation, especially pi-K separation
  - VTX reco. (for heavy flavor hadrons)

Lepton identification

- Typically Lepton id performance:
  - Isolated, high energy one: Eff > 99.5%, Mis-id rate of hadron to lepton ~ 1%.
  - Performance limited by the leptonic decay of low energy hadron, etc.

- Aim at similar performance for all leptons
  - Full energy range (1-100 GeV), full detector acceptance (|cos(θ)|<0.99).
  - For all leptons: isolated, and generated in jet (jet lepton), and even secondaries (generated from photon conversion & hadron decay)
  - The jet lepton identification is essential for the flavor physics measurements such as LFU in hadrons, etc.

$$\boxed{R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)},\ \ell = e,\ \mu}$$

$$\boxed{R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}}$$

Tau

- Identify taus in all physics events
  - Leptonic
  - Semi-leptonic one with isolated taus
  - Tau inside the jet
  - For the latter two, the identification of tau never reaches an eff*purity ~ 1;
  - Ideally: aim for eff*purity > $0.5^{1/n}$, where n is the number of objective taus (extremely difficult for $b \to s\tau\tau$ analysis...)
- Calorimeter & Tracker:
  - separate the decay products of tau.
  - Identify tau decay modes, especially in $Z \to \tau\tau$ event
- VTX: provide sufficient separation between tracks from tau-decay and background (may coming from IP, or heavy flavor hadron decays)
  - 1 prong: impact parameter
  - 3 prong: reconstructed tau decay point

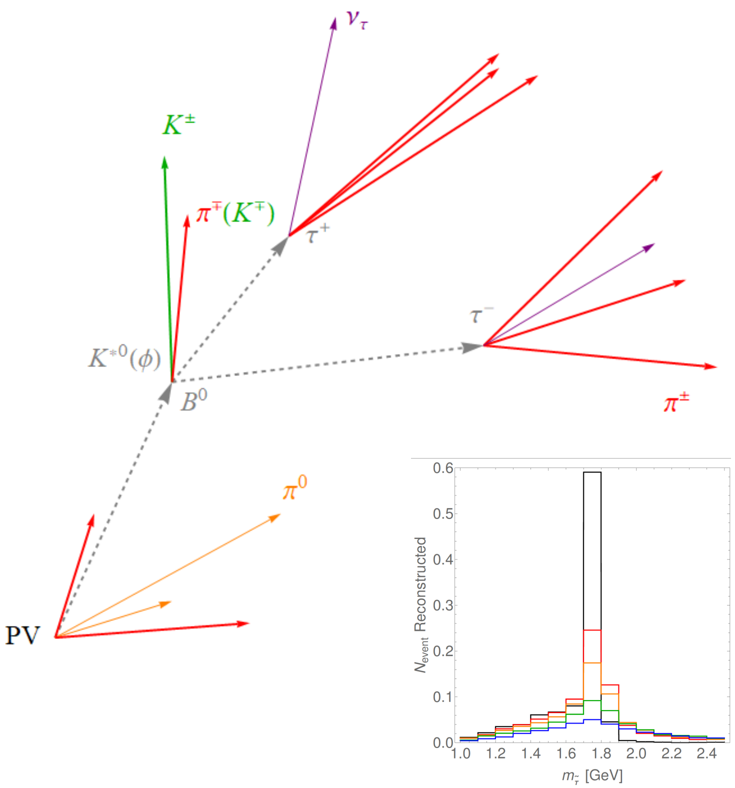
VTX

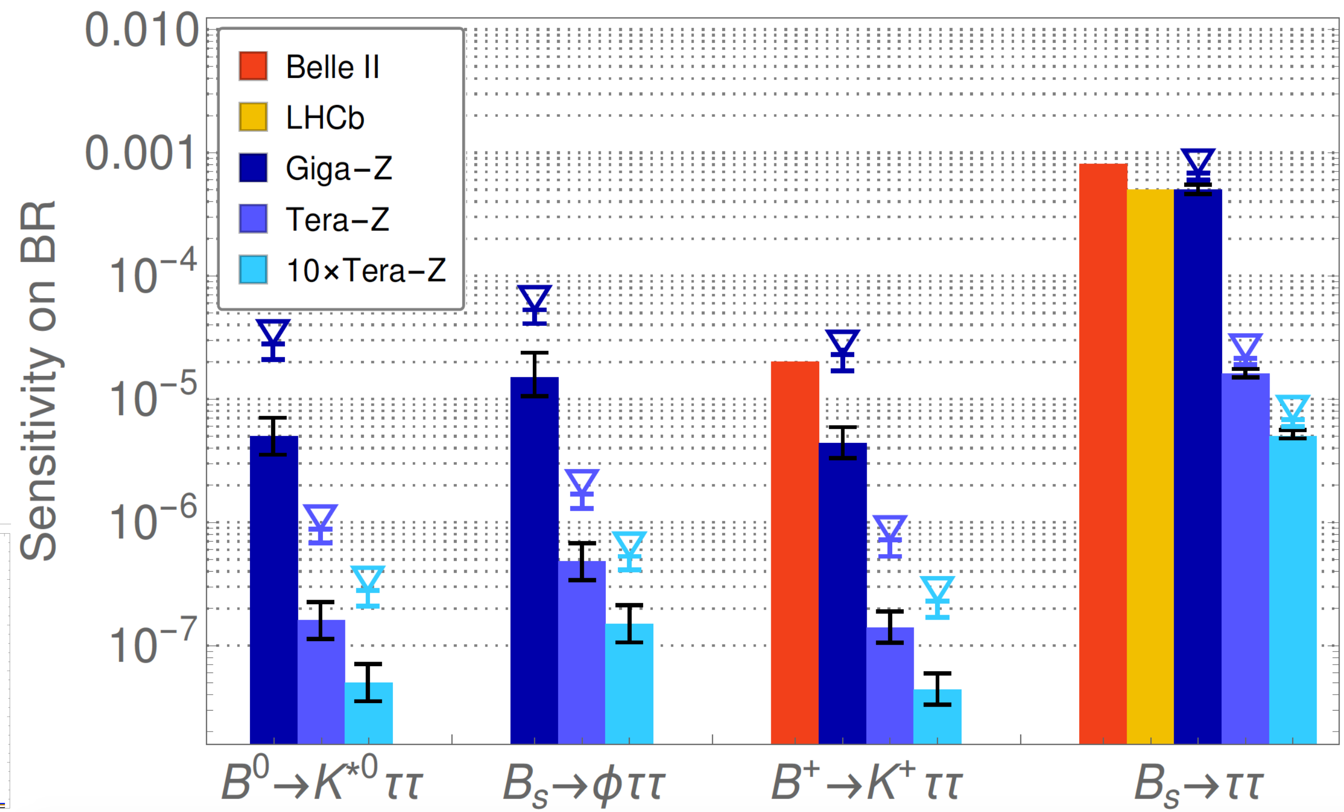
- Essential for jet flavor/charge tagging... and tau finding: need to better quantify these high-level reconstruction performance with the VTX performance (occupancy, resolution, et.al).

- Requirement 1:
  - Reconstruct & separate all displaced vertexes, i.e., reconstruct the $2^{nd}/3^{rd}$ vertex in physics benchmark of b-jet ($b \to B^* \to B \to D^* \to D \to \ldots$), if each vertex has more than 2 tracks)

- Requirement 2:
  - VTX positions need to be measured with good enough accuracy. Not only for the separation of different vertex, but also for the kinematic constrains such as the 3-prong tau vertex reconstruction in the benchmark of $b \to s\tau\tau$.

VTX: reconstruction accuracy V.S final accuracy: ideal, 1, 2, 5, 10μm resolution





LINGFENG @ HKIAS

...

Contamination of D decay that mimics tau 3-prong decay;

...

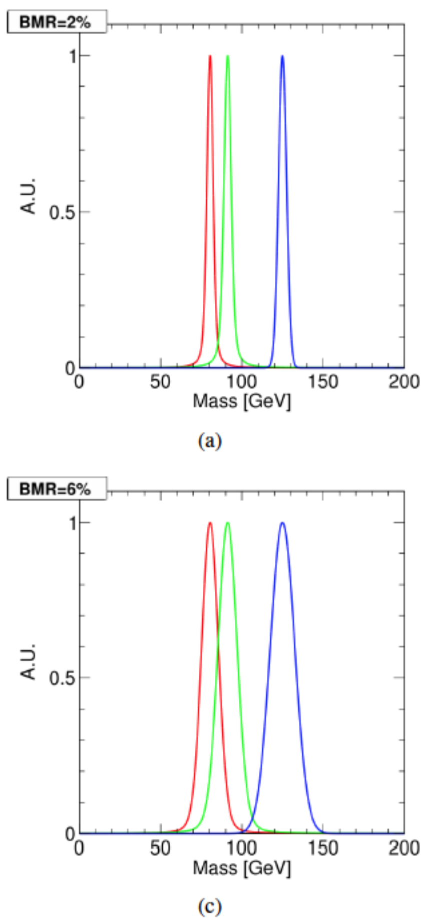
Hadronic system (jet)

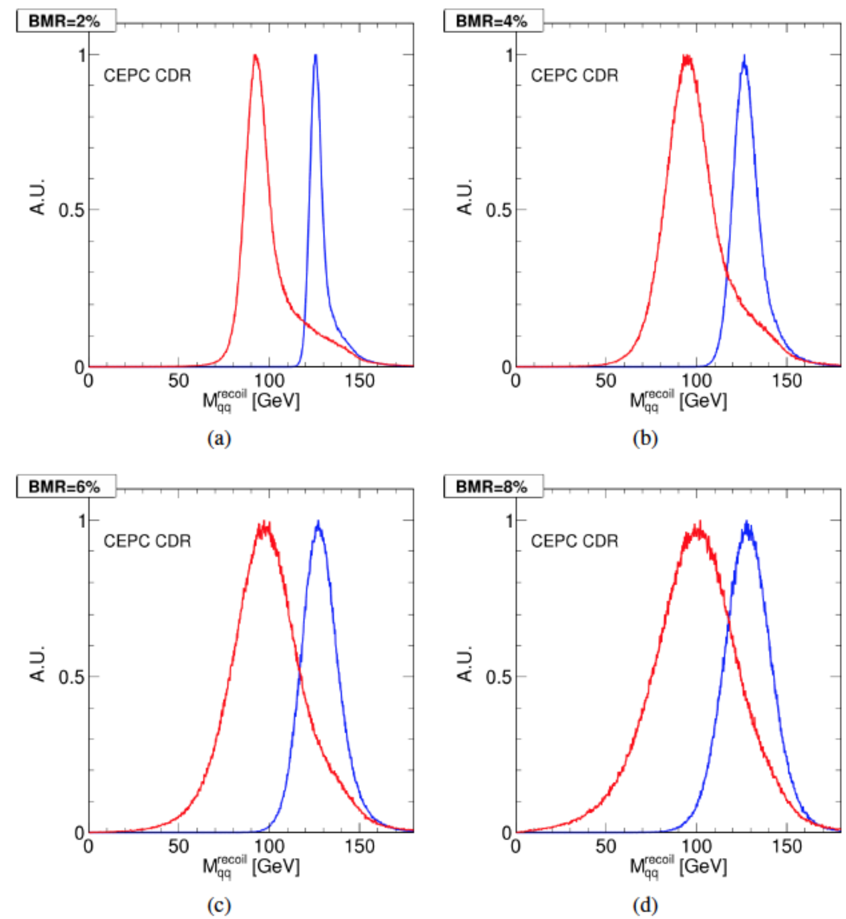
- Identify the hadronic system
  - lepton identification & missing energy measurements

- 4-momentum measurement of hadronic system - BMR: Invariant Mass Resolution of Hadronic system, benchmarked with vvH, H→gluons process),

- Jet response (Scale/Resolution of jet energy & angular observables)
  - Essential for differential measurements with jet energy/directions
    - Applied to events with more than one color singlet fragment into jets: WW/ZZ/ZH event separation in 4-jet final state
    - ...
  - Jet Clustering & Matching, or beyond?

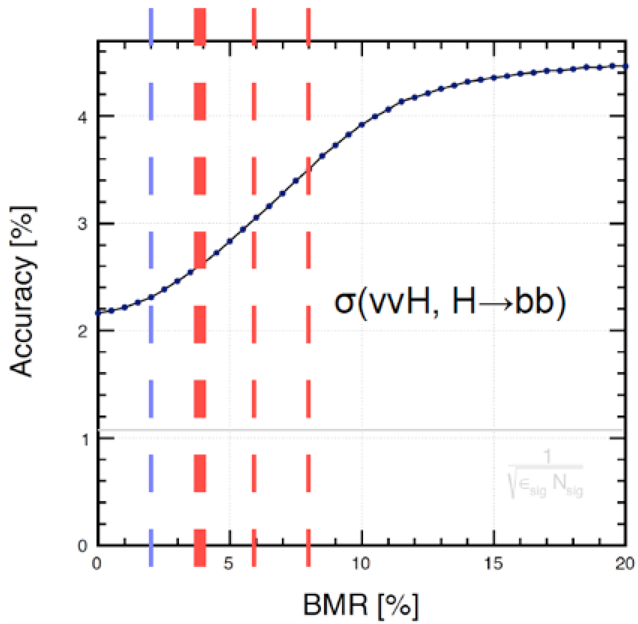
BMR < 4% required (CDR)

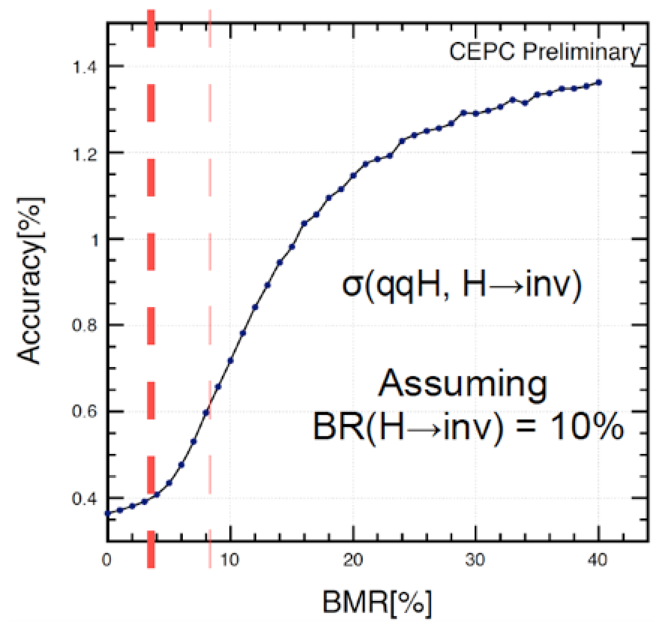


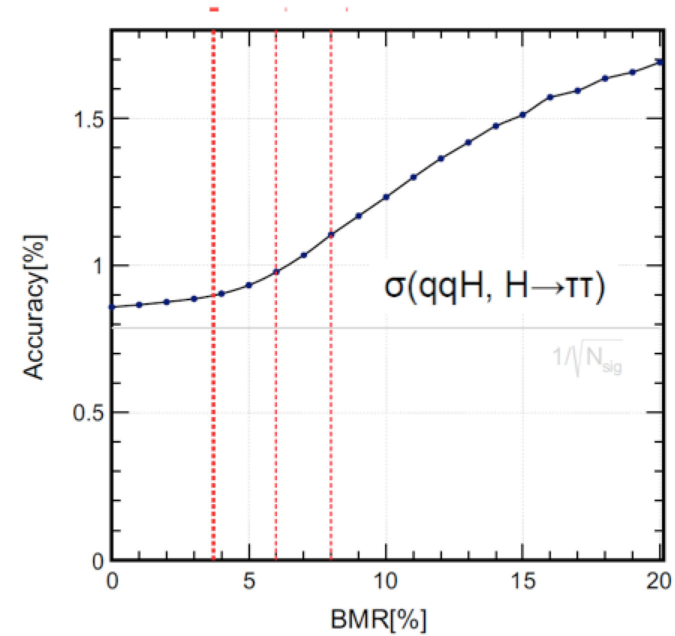


- W, Z, H mass peak separation
- To separate qqH signal from qqX background with recoil mass information

Confirmed with benchmark analyses







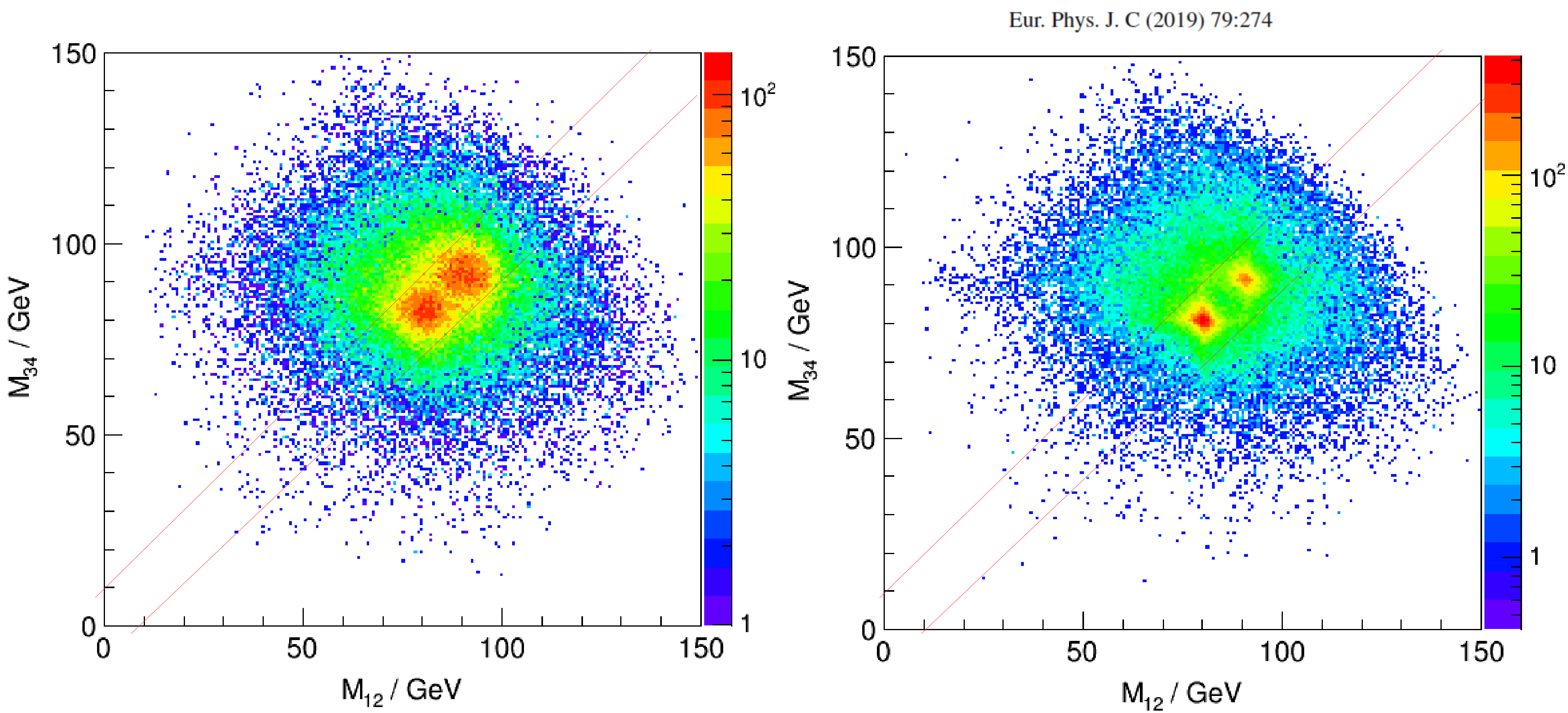
- Boson Mass Resolution: relative mass resolution of vvH, H→gg events
  - Free of Jet Clustering
  - Be applied directly to the Higgs analyses
- The CEPC baseline reaches 3.8%

	BMR = 2%	4%	6%	8%
σ(vvH, H→bb)	2.3%	2.6%	3.0%	3.4%
σ(vvH, H→inv)	0.38%	0.4%	0.5%	0.6%
σ(qqH, H→ττ)	0.85%	0.9%	1.0%	1.1%

Hadronic system: more than 2 jets?

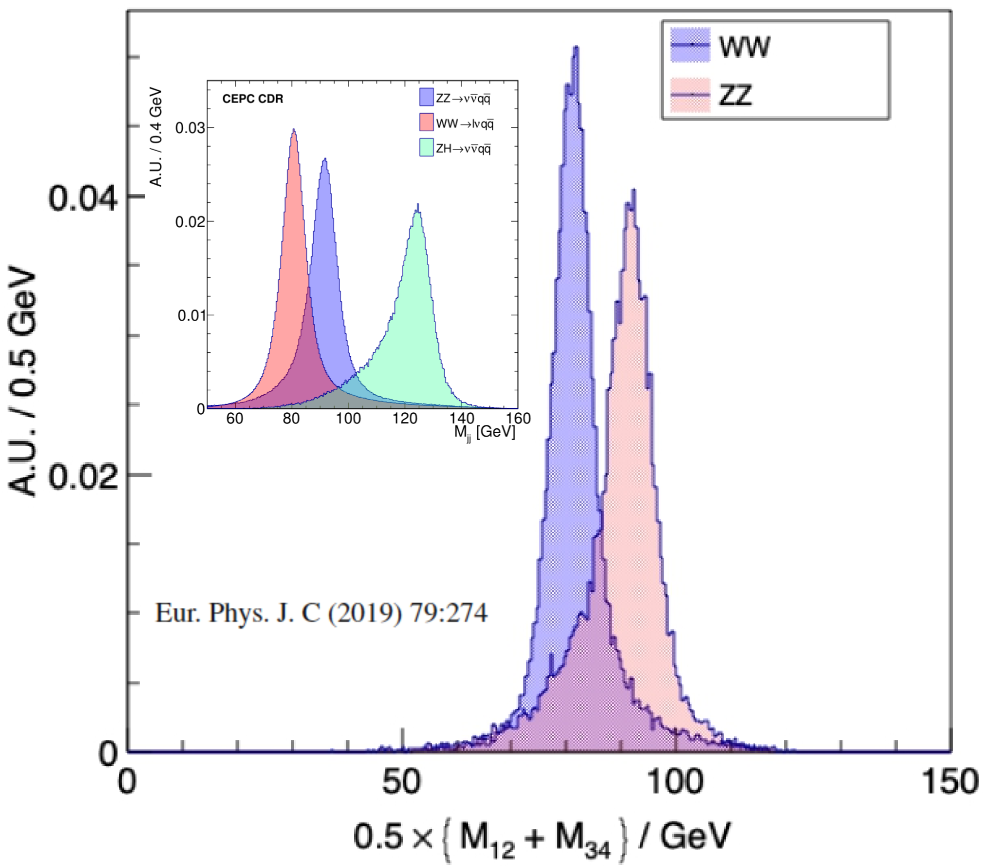
- Matching the final state particles to the colored partons (quarks, gluon, etc) can induce significant uncertainties
- For physics event with multiple color singlets that decay hadronically, how to identify all the final state particles corresponding to one color singlet?
  - i.e., Essential for full hadronic ZH, ZZ, WW events separation
- Conventionally: Jet Clustering & Matching
  - Dominant the performance in physics benchmark of full hadronic WW/ZZ separation at the CEPC baseline detector
  - Goes beyond?

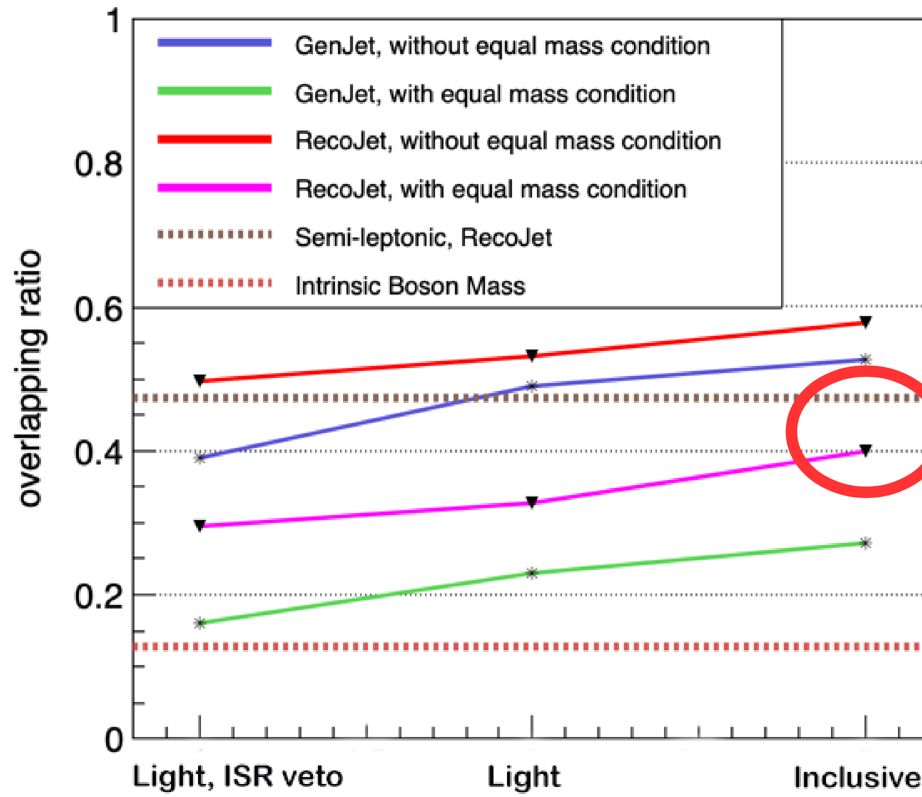
Reconstructed mass of the two di-jet system



Equal mass condition |M12 – M34| < 10 GeV: At the cost of half the statistic, the overlapping ratio can be reduced from 58%/53% to 40%/27% for the Reco/Genjet

Separation of full hadronic WW-ZZ event





The CEPC Baseline could separate efficiently the WW-ZZ with full hadronic final state.

Critical to develop color singlet reconstruction: improve from the naive Jet clustering & pairing.

Quantified by differential overlapping ratio.

Control of ISR photon/neutrinos from heavy flavor jet is important.

Summary

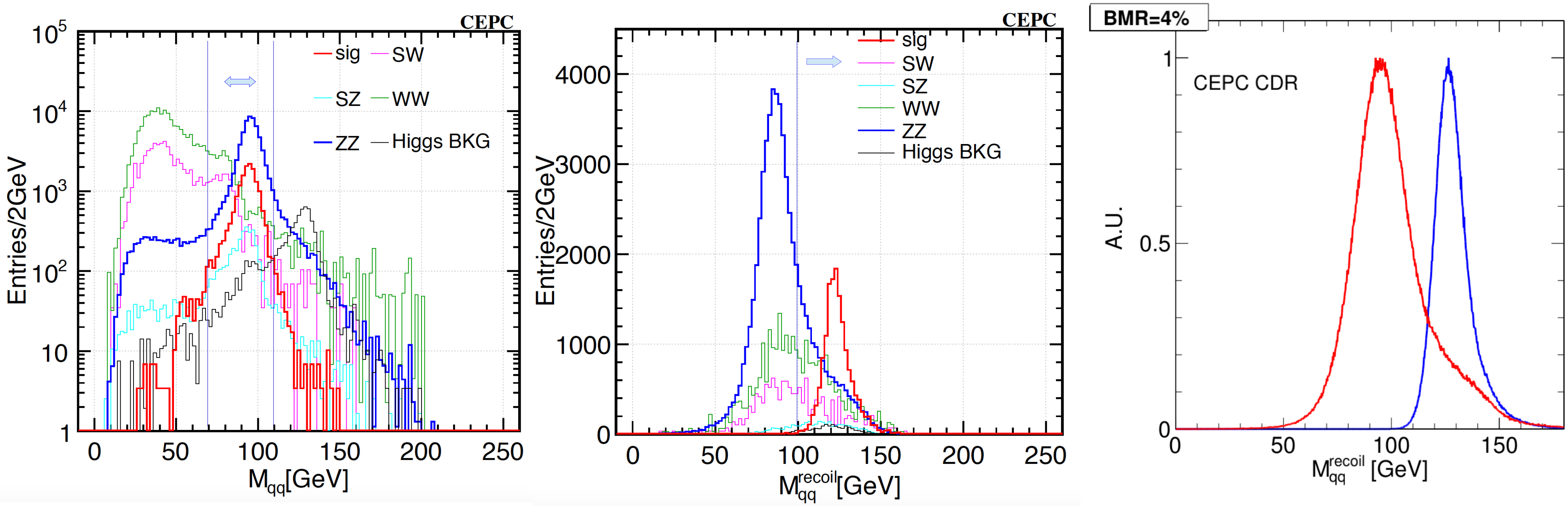
- The CEPC, a high precision Higgs/Z factory, has very rich physics program and multiple stringent requirements on its detector performance
- Higgs factory:
  - Hadronic system
    - The majority of Higgs events has jet final states; many important EW measurements relies on multi-jet processes.
    - BMR < 4%: to separate qqH signal from qqX background with recoil mass
    - To investigate innovative color singlet identification algorithm (optimize jet clustering-matching or beyond)
  - Relative track momentum resolution ~ 0.1%
  - Isolated Leptons and taus;
    - Isolated leptons: eff*purity > 99% (eff > 0.995%, mis-id < 1%);
    - Isolated Tau finding: eff*purity > 70%.
  - VTX: efficiently separate the b, c, and light jets.
    - eff*purity of c-tagging at $H \rightarrow jj$ events. Aim for eff*purity >> 10% (i.e. 25%?)

Summary

- Z factory: finding objects inside jets...
  - Tracks: energy threshold ~o(100) MeV, $\delta p/p << 0.1\%$;
  - Photon: energy threshold ~o(100) MeV;
  - π^0 reconstruction:
    - separate photons from 30 GeV π^0, count $\#\pi^0$ in tau decay.
    - EM resolution of ~5%/sqrt(E), for π^0 finding in hadronic events
  - Leptons: eff > 99.5% & mis-id < 1% for all leptons, especially jet leptons
  - 3σ Pi-K separation up to 20 GeV, to identify hadrons decay into kaon & proton
  - VTX: to reconstruct all 2nd vertex (with more than 2 tracks) with sufficient accuracy.
    - Identify & characterize the b-jet ($b \rightarrow B^* \rightarrow B \rightarrow D^* \rightarrow D \rightarrow$...), c-jet, light jets...
    - Separate 3 prong tau from D background
    - Need to associate those requirements on VTX performance (position, efficiency, occupancy...)
  - Missing energy/momentum measurements
- In general: Z factory has extremely rich physics program, and a better detector always leads to better physics reach. More benchmark study & iterations are needed, to further quantify the Z factory physics potential & corresponding requirements.

Back up

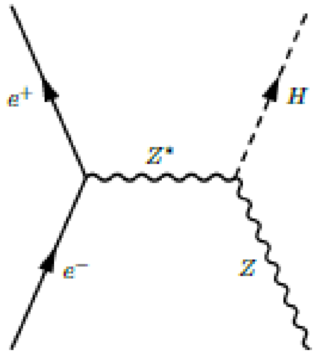
g(Hττ) at qqH: di-jet and VTX information

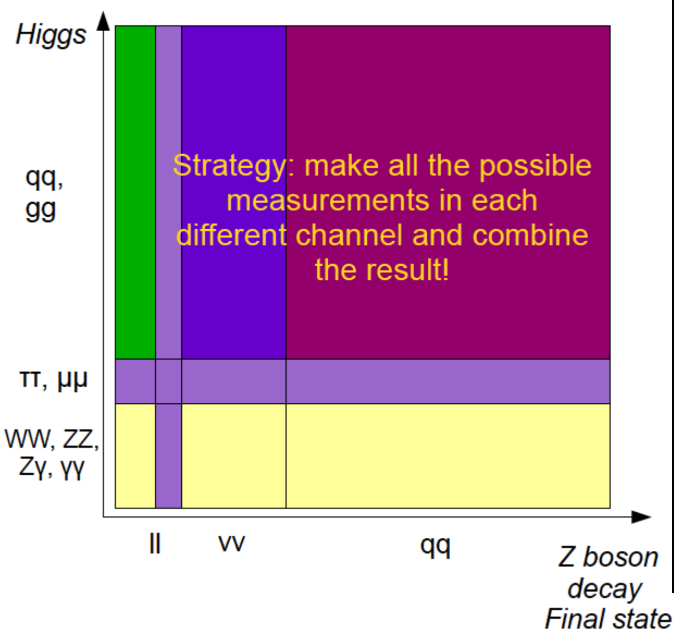


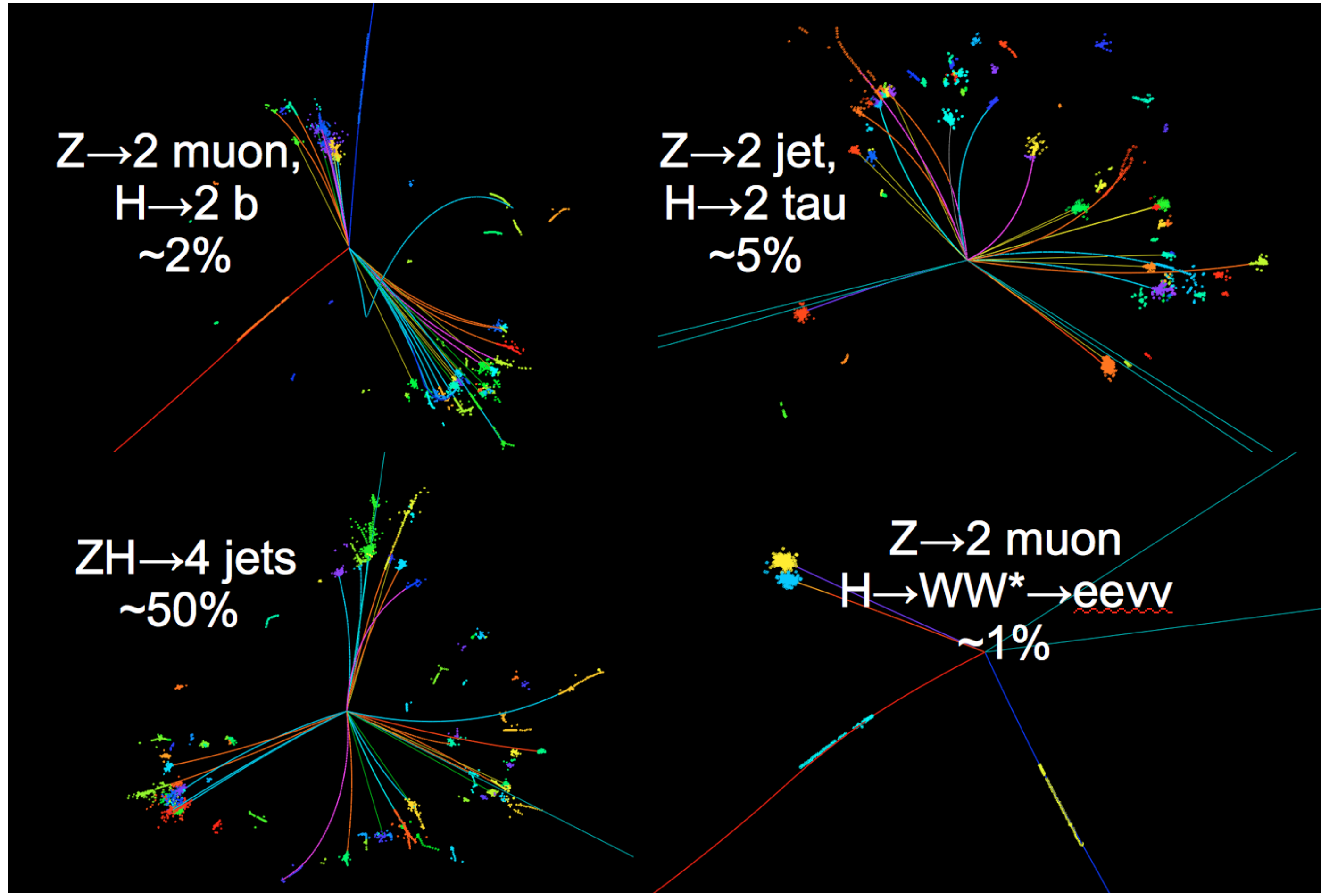
- TAURUS: di-tau system
- The rest particles are identified as the di-jet: to distinguish the ZZ/ZH background & Improves the accuracy by more than a factor of 2: **BMR < 4% (baseline of 3.8%) is crucial**
- Isolated tracks are intensionally defined as tau candidate: be distinguished by the VTX
- Relative accuracy of 0.9% at 5.6 ab^{-1} integrated luminosity, dominate the combined accuracy (0.8%)

Dan Yu's thesis

Physics Requirements







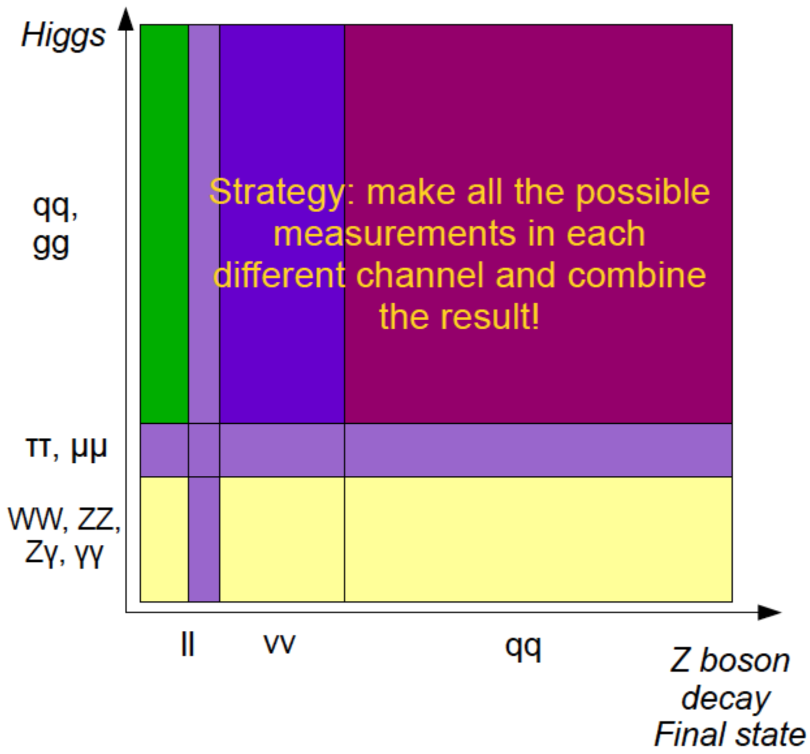
Detector:

To reconstruct all the physics objects with high efficiency, purity & resolution

Homogenous & Stable enough to control the systematic

Jets at the Higgs Signal

- SM Higgs
  - **0 jets: 3%**
    - Z→ll, νν (30%); H→0 jets (~10%, ττ, μμ, γγ, γZ/WW/ZZ→leptonic)
  - **2 jets (+n with gluon emission...): 32%**
    - Z→qq, H→0 jets. 70%*10% = 7%
    - Z→ll, νν; H→2 jets. 30%*70% = 21%
    - Z→ll, νν; H→WW/ZZ→semi-leptonic. 3.6%
  - **4 jets: 55%**
    - Z→qq, H→2 jets. 70%*70% = 49%
    - Z→ll, νν; H→WW/ZZ→4 jets. 30%*15% = 4.5%
  - **6 jets: 11%**
    - Z→qq, H→WW/ZZ→4 jets. 70%*15% = 11%



- 97% of the SM Higgsstrahlung Signal involves Jets
- 66% need color-singlet identification: grouping the hadronic final sate particles into color-singlets (Z, H, W, gamma, ...).

Jets at the Higgs Signal

- SM Higgs
  - **0 jets: 3%**
    - Z→ll, vv (30%); H→0 jets
  - **2 jets: 32%**
    - Z→2 jets, H→0 jets. 7%
    - Z→0 jets; H→2 jets. 21%
    - Z→0 jets; H→VV→semi-leptonic. 3.6%

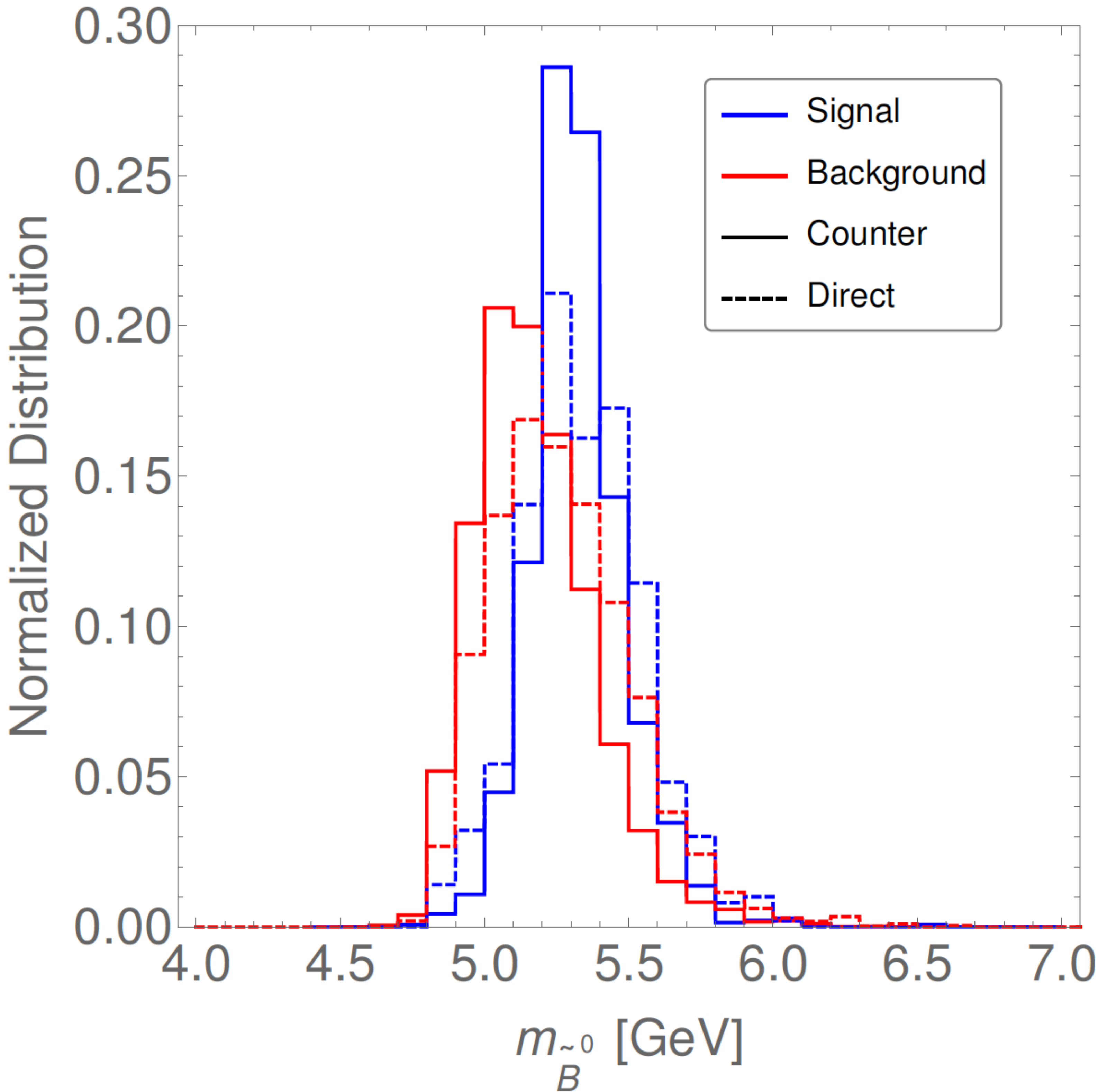
- 1/3 of the Higgsstrahlung events
  - Have access to all SM Higgs decay modes
  - Doesn't need color singlet identification: No hadronic final states, or only 1 color singlet thus naturally identified

---

  - **4 jets: 55%**
    - Z→2 jets, H→2 jets + X. 49%
    - Z→0 jets; H→WW/ZZ→4 jets. 4.5%
  - **6 jets: 11%**
    - Z→qq, H→WW/ZZ→4 jets. 11%

- 2/3 of the Higgsstrahlung events
  - Dominate statistic of H→bb, cc, gg, WW, ZZ, Zγ
  - Color singlet identification – **potentially a leading systematic, huge impact**

- Jet clustering is essential for any measurements concerning jet direction (differential measurements)


0.30
0.25
0.20
0.15
0.10
0.05
0.00
Normalized Distribution
Signal
Background
Counter
Direct
4.0
4.5
5.0
5.5
6.0
6.5
7.0
$m_{\tilde{B}^0}$ [GeV]